Detailed Model Description

This section describes the variables, constraints, and other attributes in the linear program formulation of WinDS. It outlines, in order:

1. Subscripts (variables and constraints)
2. Major decision variables
3. The objective function
4. Constraints
5. Wind intermittency parameters
6. Retirement of capacity
7. Financial parameters

1. Subscripts

We list the major subscripts below:

Regional

Wind supply and demand regions are denoted by **i** or **j**. They are referred to both as wind supply and wind demand, because we track both where the wind power is generated and to where it is transmitted. This allows us to ensure adequate transmission capacity is available to exit the supply region and to enter the demand region. It also allows us to ensure that the wind generation consumed in a power control area (PCA) is distributed throughout the PCA and not just at the closest point to the wind supply region. There are 358 wind supply/demand regions.

PCAs are denoted by **p** and **n**. There are 136 PCAs, each of which contains one or more wind supply/demand regions.

NERC regions/subregions are denoted by **r.** There are 13 NERC regions/subregions, each of which contains several PCAs.

Interconnection areas are denoted by **in**. There are three interconnect regions, each of which contains one or more NERC regions.

Time

Time slices are denoted by **m**. There are 16 time slices during each year, with four seasons and four daily time slices in each season. (We use the word “slice” to distinguish from the 2-year “periods” for which the LP is run between 2000 and 2050.)

Seasons are denoted by **s**. There are four seasons.

Technology/Resource

Wind resource classes: Wind classes are denoted by **c**. There are five wind classes (3-7).

Conventional generator types are denoted by **q**. There are 14 different types of conventional generators

2. Major decision variables

The major decision variables include new wind capacity, wind storage, conventional capacity, and dispatch of conventional capacity.

Note: Variables that denote capacity are expressed in megawatts and begin with capital letters. Variables that denote energy are expressed in megawatthours and begin with lower-case letters.

Wind

There are three types of wind capacity in WinDS—onshore, shallow offshore, and deep offshore. They are distinguished by different costs (capital and operating) and performance (capacity factors). Within each of these types, there are additional categories—based on whether the wind generation is transmitted on existing[1] (in 2000) transmission lines or new transmission lines built specifically for the wind generation. Wind generation transmitted on new dedicated transmission lines is further disaggregated into that used within the same region as the wind site, and that transmitted from one wind supply/demand region to another.

Onshore wind

$\mathbf{WturN_{i,wscp}}$ New[2] onshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscp of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of wind to be used from region i is selected before the LP is run for the current period; i.e. in WinDS, only one class of onshore wind on existing lines is allowed to be built in any specific region in any one 2-year period. This is done to reduce the number of variables in the LP.

$\mathbf{WturTN_i}$ New onshore wind turbine capacity (MW) that can be transmitted only on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of onshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a wscp subscript, because there is no supply curve associated with building dedicated transmission all the way to the destination region (as opposed to building to a connecting point with the existing grid). The new transmission for this new wind capacity is assumed to be built from the center of region i to the center of a different destination region.

$\mathbf{Wtur\_inregion_{c,i}}$ New onshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e. the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

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[1] For the purposes of this document, the word "existing" means in existence at the start of the modeled time, i.e. in existence in the year 2000.
[2] New capacity means capacity built in this period, i.e. in this period's optimization run of the linear program.

$WN_{i,j}$ New onshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid. This variable allows WinDS to track the source of all wind coming into a region j so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output. This variable differs (has a value less than or equal to) from $WturN_{i,wscp,}$ in that some of the capacity represented by $WturN_{i,wscp}$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the grid.

$WTN_{i,j}$ New onshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission. This variable differs (has a value less than or equal to) from $WturTN_i$, in that some of the capacity represented by $WturTN_i$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the destination region.

$WNSC_{i,wscp}$ New onshore wind turbine capacity (MW) to be connected to the grid in region i from step wscp of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WN_{i,j}$ (i.e., not having a variable $WN_{c,i,j}$ with three subscripts), the total number of variables is reduced.

$WELEC\_inregion_{c,escp,i}$ New onshore wind turbine capacity (MW) from a class c wind site on step escp of the supply curve within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i. This variable differs (has a value less than or equal to) from $Wtur\_inregion_{c,i,}$ in that some of the capacity represented by $Wtur\_inregion_{c,i}$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the grid.

$wind\_2\_electrolysis_{c,i,s}$ Class c wind generation (MWh) from new wind turbines that connect to the grid (not directly to load distribution systems) supplied to the new conversion to storage (e.g., electrolyzers/hydrogen storage) in season s in region i.

$grid\_2\_welectrolysis_{i,m}$ Grid-supplied electricity (MWh) to new wind storage (e.g., electrolyzers/hydrogen storage) at grid-connected wind farms in region i in time slice m.

$wind\_2\_electrolysis\_inregion_{c,i,s}$ Wind-generated electricity (MWh) from class c new turbines in region i in season s that goes to storage (e.g., electrolyzers/hydrogen storage) at a wind site that is not connected to the grid, but is connected by new lines directly to the distribution system at a load center.

$grid\_2\_welectrolysis\_inregion_{i,m}$ Grid-supplied electricity (MWh) to new wind storage (e.g., electrolyzers/hydrogen storage) at “inregion” wind farms in region i in time slice m.

WCt_g New onshore national wind turbine capacity (MW) in bin g; used for estimating the increase in wind turbine price with rapid world growth

$WCtinst_{ginst,i}$ New onshore wind turbine capacity (MW) from bin ginst in region i; used for estimating the increase in installation costs with rapid regional growth

Shallow offshore wind

The shallow offshore wind variables are similar to the onshore variables, with the exception that on-site storage (e.g., electrolyzers/hydrogen storage) is not allowed.

$WturNofs_{i,wscpofs}$ New shallow offshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscpofs of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of shallow offshore wind to be used from region i is selected before the LP is run for the current period, i.e. in WinDS only one class of shallow offshore wind on existing lines is allowed to be built in any specific region in any one 2-year period. This is done to reduce the number of variables in the LP.

$WturTNofs_i$ New shallow offshore wind turbine capacity (MW) that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of shallow offshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a “wsc” subscript, because there is no supply curve associated with building dedicated transmission all the way to the receiving region (as opposed to building to the nearest grid connection). The new transmission is assumed to be built from the center of region i to the center of a different destination region.

$Wtur\_inregionofs_{c,i}$ New shallow offshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e., the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

$WNofs_{i,j}$ New shallow offshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid. This variable allows WinDS to track the source of all wind coming into a region j, so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output.

$WTNofs_{i,j}$ New shallow offshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission.

$\mathbf{WELEC\_inregionofs}_{c,escp,i}$ New shallow offshore wind turbine capacity (MW) from class c wind site from supply step escp within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i.

$\mathbf{WNSCofs}_{i,wscpofs}$ New shallow offshore wind turbine capacity (MW) connected to the grid in region i from step wscpofs of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WNofs_{i,j}$ i.e. not having a variable $WNofs_{c,i,j}$ with three subscripts, the total number of variables is reduced.

Deep offshore wind

The deep offshore wind variables are similar to the onshore variables with the exception that on-site storage (e.g., electrolyzers/hydrogen storage) is not allowed.

$\mathbf{WturNofd}_{i,wscpofd}$ New deep offshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscpofd of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of deep offshore wind to be used from region i is selected before the LP is run for the current period, i.e. in WinDS, only one class of deep offshore wind on existing lines is allowed to be built in a region in any one 2-year period. This is done to reduce the number of variables in the LP.

$\mathbf{WturTNofd}_{i}$ New deep offshore wind turbine capacity (MW) that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of deep offshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a wscp subscript, because there is no supply curve associated with building dedicated transmission all the way to the receiving region (as opposed to building to the nearest grid connection). The new transmission is assumed to be built from the center of region i to the center of a different destination region.

$\mathbf{Wtur\_inregionofd}_{c,i}$ New deep offshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e., the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

$\mathbf{WNofd}_{i,j}$ New deep offshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid.

This variable allows WinDS to track the source of all wind coming into a region j, so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output.

$WTNofd_{i,j}$ New deep offshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission.

$WELEC\_inregionofd_{c,escp,i}$ New deep offshore wind turbine capacity (MW) for a class c wind site from supply step escp within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i.

$WNSCofd_{i,wscpofd}$ New deep offshore wind turbine capacity (MW) to be connected to the grid in region i from step wscpofd of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WNofd_{i,j}$ i.e., not having a variable $WNofd_{c,i,j}$ with three subscripts, the total number of variables is reduced.

Wind storage

ELE_i New capacity (MW) at the onshore wind site in region i for converting the wind-generated electricity to the storage medium. For hydrogen, ELE represents the electrolyzer capacity.[3]

$H2storagecapacity_i$ New storage (hydrogen) capacity in region i.

$fcellcapacity_i$ New generation capacity (MW) fueled by the storage medium generated from onshore wind in region i. For hydrogen, this is the fuel cell capacity.

$fcell_{i,r,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) in wind supply region i for use in NERC region r during season s. Because it is assumed that the stored energy is converted to electricity only during the peak electric time slice of each season, it is not necessary to keep track of the specific time slice during which the stored energy is used to produce electricity, but only the season. The destination of the stored energy is tracked only to the NERC region destination to reduce the number of decision variables.

$fcell\_inregion_{c,i,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) filled by class c wind resources in wind

[3] All the variable names associated with wind storage are based on hydrogen. For example, ELE stands for electrolyzer. However, they can also represent the conversion necessary for other forms of storage. For example, in a compressed-air energy system, ELE would be the compressor needed to convert the wind-generated electricity to compressed air.

supply region i for use in the same wind demand region i during season s. The class subscript c ensures that an energy balance can be maintained by wind class between the amount of wind energy coming into storage from each wind class and the amount going out of storage. Because wind storage is assumed to be used to generate electricity only during peak electric-load time slices, the seasonal subscript s completely defines the time slice in which the generation occurs.

$fcelldest_{n,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) consumed in PCA n in season s. Inasmuch as wind storage is assumed to be used to generate electricity only during peak electric-load time slices, the seasonal subscript s completely defines the time slice in which the generation occurs. This variable could have been subscripted i,n,s and replaced the variable $fcell_{i,r,s}$, but that would have added more than 175,000 more variables (4*358*[136-13]) (see the constraint "FUEL_CELL_BALANCE" in the equations that follow this section)

$HEGBIN_{hebp}$ New national capacity (MW) for conversion from wind generation to stored energy (i.e. electrolyzer capacity) in growth bin hebp; used for estimating the increase in price with rapid growth.

$HFCGBIN_{hfcbp}$ New national capacity (MW) for conversion from stored energy to electricity in growth bin hfcbp (i.e. fuel cell capacity); used for estimating the increase in price with rapid growth

Hydrogen fuel

hfs_i Hydrogen fuel (kg) produced in region i from new onshore wind installations that are connected to the grid.

hfd_j Hydrogen fuel (kg) consumed in region j and produced by new wind installations connected to the grid.

$hf_{i,j}$ Hydrogen fuel (kg) shipped from new onshore wind installations in region i that are connected to the grid to region j.

$hf\_inregion_{c,hscp,i}$ Hydrogen fuel (kg) produced from class c wind in region i from step hscp for the supply curve that provides the cost of hydrogen shipment from wind in the region to city load centers within the same region i.

$HF\_DISELEC\_CAP_j$ New distributed storage (e.g., electrolyzers/hydrogen storage) capacity (kg/year) powered by the grid and located at load center j (as opposed to ELE_j, which is powered by wind and the grid and located at a wind site).

$hfdiselec_j$ Hydrogen fuel (kg) produced by both new and old distributed electrolyzers in region j for use as a transportation fuel. Does not include hydrogen stored for use in a distributed fuel cell.

$hfdiselec\_2\_fcell_{j,m}$ Hydrogen fuel (kg) produced by both new and old distributed storage (e.g., electrolyzers/hydrogen storage) in region j for storage for later use in a generator (e.g., fuel cell) in time slice m.

$HF\_STEAMREF\_CAP_j$ New steam methane reformer capacity (kg/year) in region j.

$hfsteamref_j$ Hydrogen fuel (kg) produced by both new and old steam methane reformers in region j.

$DISFCELL\_CAP_n$ New distributed fuel cell capacity (MW) within PCA n using hydrogen from the distributed electrolyzers $HF\_DISELEC\_CAP_j$ and steam methane reformers $HF\_STEAMREF\_CAP_j$ that are in demand regions j within PCA n. These distributed fuel cells are accounted for at the PCA level (n) rather than the wind supply/demand region level (j) to reduce the number of variables.

Conventional generation

$CONVCAP_{n,q}$ Total conventional capacity (MW) in PCA n[4] of type q.

$CONVGEN_{m,n,q}$ Total conventional capacity (MW) from plants of type q operating in time slice m in PCA n.

$CONVPGEN_{m,n,q}$ Total conventional capacity (MW) from plants in PCA n of type q that is in excess of the conventional generation that operates in nonpeak time slices ($CONVPGEN_{m,n,q}$. will be zero for off-peak time slices). This variable allows additional costs to be incorporated for the use of base and intermediate load technologies that are operated at higher levels during peak time slices than in other time slices. These additional costs reflect the fact that for a coal plant to generate more power on peak, it will have to buy fuel to ramp up before the peak time slice and down after the slice (WinDS also includes a constraint that ensures that any base generator incurs the costs

[4] Note that, for conventional capacity, the decision variable is not the new capacity, but the total capacity. This was done to simplify bookkeeping and to eliminate the need for vintaging of capacity built after 2000. To ensure that conventional capacity from previous periods (minus retirements) is built, a lower bound is specified for each of these variables. The objective function value from the LP is inaccurate, in that the cost of the conventional generators is incurred each period, but this does not affect the amount of conventional capacity installed, because anything built beyond the lower bound must pay the marginal cost of new capacity. It does affect the amount of conventional fuel purchased, in that the old capacity is assumed to have the same heat rate as the new capacity. On the other hand, it does ensure that the marginal cost of new capacity accurately reflects the heat rate of the newest units. For coal-fired generators, vintage is tracked through the existence of four types of coal plants, pre-2000 plants with scrubbers, pre-2000 plants without scrubbers, post-2000 pulverized coal plants, and post-2000 integrated gasification combined cycle plants.

associated with $CONVPGEN_{m,n,q}$ by preventing $CONVGEN_{m,n,q}$ from being larger in peak time slices than in the average of the two shoulder time slices surrounding the peak).

$coalowsul_{n,q}$ Total conventional generation (MWh) from coal plants in PCA n of type q using low-sulfur coal.

QSq,n Total capacity (MW) in PCA n of type q that has been modified to provide quick-start capability.

$SR_{m,n,q}$ Total spinning reserve capacity (MW) available in time slice m in PCA n by generator type q.

Dispatchable load

IL_n Interruptible load (MW) in PCA n

$ILt_{ilg,n}$ Interruptible load (MW) from supply curve step ilg used in PCA n.

Transmission

$CONVT_{m,n,p}$ Total conventional capacity (MW) transmitted in time slice m from PCA n to PCA p.

$WT_{n,p}$ Total wind capacity (MW) transmitted from PCA n to PCA p.[5]

$TPCAN_{n,p}$ New transmission line capacity (MW) built to carry new generation between PCA n and PCA p.

$CONTRACTCAP_{n,p}$ Total firm capacity (MW) contracted to be supplied to PCA n by PCA p.

$TPCA\_Ct_{tpca\_g}$ New transmission capacity (MW) in growth bin tpca_g; used for estimating the increase in new transmission line price with rapid growth.

[5] Without this variable, WinDS will ship power from wind supply region i to the closest wind demand region j; and, from there, continue to ship it as conventional power to other PCAs where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different PCA, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

3. Objective function

The objective function of the linear program of WinDS is to minimize the following costs:

Capital costs of new wind plants
+ Operating costs of all wind generation (including forecast/bidding penalties)
+ Cost of transmission of wind (old and new lines)
+ Cost of storing wind power
+ Capital cost of new conventional plants
+ Fuel and operating costs of conventional generation
+ Cost of spinning reserve
+ Cost of interruptible loads

In equation form with explanatory notes in [brackets]:

$$[Wind\_onshore\_capital\_\cos ts\_and\_O\&M\_\cos ts]$$
$$\sum_{c,i}(CW_c(1+cslopeW\cos tfactor*cslope_{c,i})+CWOM_c)*(\sum_{wscp}WturN_{i,wscp}*class_{c,i}+WturTN_i*classT_{c,i}+Wtur\_inregion_{c,i})$$
$$[Wind\_offshore\_shallow\_capital\_\cos ts\_and\_O\&M\_\cos ts]$$
$$+\sum_{c,i}(CWcofs_c+CWOMcofs_c)*(\sum_{wscpofs}WturNofs_{i,wscpofs}*classofs_{c,i}+WturTNofs_i*classTofs_{c,i})$$
$$[Wind\_offshore\_deep\_capital\_\cos ts\_and\_O\&M\_\cos ts]$$
$$+\sum_{c,i}(CWcofd_c+CWOMcofd_c)*(\sum_{wscpofd}WturNofd_{i,wscpofd}*classofd_{c,i}+WturTNofd_i*classTofd_{c,i})$$
$$[Cost\_to\_connect\_onshore\_wind\_to\_the\_grid]$$
$$+\sum_{i,c}Cgridconnect*(\sum_{j}WN_{i,j}*class_{c,i}+WTN_{i,j}*classT_{c,i}+\sum_{escp}Welec\_inregion_{c,escp,i})$$
$$[Cost\_to\_connect\_offshore\_shallow\_wind\_to\_the\_grid]$$
$$+\sum_{i,c}Cgridconnect*(\sum_{j}WNofs_{i,j}*classofs_{c,i}+WNofs_{i,j}*classTofs_{c,i})$$
$$[Cost\_to\_connect\_offshore\_shallow\_wind\_to\_the\_grid]$$
$$+\sum_{i,c}Cgridconnect*(\sum_{j}WNofd_{i,j}*classofd_{c,i}+WNofd_{i,j}*classTofd_{c,i})$$

$$Wind\_transmission\_\cos t\_on\_existing\_transmission\_lines\_throughout\_analysis\_period]$$

$$+(TOWCost*dis_{i,j}+POSTSTWCOST*PostStamp_{i,j})*(\sum_{c,i,j}WN_{i,j}*class_{c,i}*CF_c+WNofs_{i,j}*classofs_{c,i}*CFcofs_c$$

$$+WNofd_{i,j}*classofd_{c,i}*CFcofd_c)*8760*PVA_{d_r,E}*(1-IWSurplusMar_{c,i\in in})$$

$$[Cost\_of\_new\_transmission\_lines\_dedicated\_to\_wind]$$

$$+TNWCost*(1+(cslope_{c,i}+cslope_{c,j})/2*cslopeT\cos tfactor)*(cpop_{c,i}+cpop_{c,j})/2*\max(50,dis_{i,j})$$

$$*\sum_{c,i,j}(WTN_{i,j}*classT_{c,i}+WTNofs_{i,j}*classTofs_{c,i}+WTNofd_{i,j}*classTofd_{c,i})$$

$$[Cost\_of\_new\_transmission\_lines\_from\_the\_wind\_site\_to\_the\_grid\_$$
$$throughout\_the\_analysis\_period]$$

$$+\sum_{c,i,wscp}(WNSC_{i,wscp}*class_{c,i}*WR2GPTS_{c,i,wscp})*CF_c*8760*PVA_{d_r,E}$$

$$[Cost\_of\_new\_transmission\_lines\_from\_the\_shallow\_offshore\_wind\_site\_to\_the\_grid\_$$
$$throughout\_the\_analysis\_period]$$

$$+\sum_{c,i,wscp}(WNSCofs_{i,wscp}*classofs_{c,i}*WR2GPTSofs_{c,i,wscp})*CFcofs_c*8760*PVA_{d_r,E}$$

$$[Cost\_of\_new\_transmission\_lines\_from\_the\_deep\_offshore\_wind\_site\_to\_the\_grid\_$$
$$throughout\_the\_analysis\_period]$$

$$+\sum_{c,i,wscp}(WNSCofd_{i,wscp}*classofd_{c,i}*WR2GPTSofd_{c,i,wscp})*CFcofd_c*8760*PVA_{d_r,E}$$

$$[[Cost\_of\_building\_new\_transmission\_lines\_to\_load\_centers\_in\_the\_same\_region\_$$
$$as\_the\_wind]$$

$$+\sum_{c,escp,j}Welec\_inregion_{c,escp,j}*MW\_inregion\_dis_{c,escp,j}*(1+cslope_{c,j}*cslopeT\cos tfactor)*cpop_{c,j}$$
$$*CF_c*8760*PVA_{d_r,E}$$

$$[Cost\_of\_building\_new\_transmission\_lines\_to\_load\_centers\_in\_the\_same\_region\_$$
$$as\_the\_shallow\_offshore\_wind]$$

$$+\sum_{c,escpofs,j}Welec\_inregionofs_{c,escpofs,j}*MW\_inregion\_disofs_{c,escpofs,j}*cpop_{c,j}*CFofs_c*8760*PVA_{d_r,E}$$

$$[Cost\_of\_building\_new\_transmission\_lines\_to\_load\_centers\_in\_the\_same\_region\_$$
$$as\_the\_deep\_offshore\_wind]$$

$$+\sum_{c,escpofd,j}Welec\_inregionofd_{c,escpofd,j}*MW\_inregion\_disofd_{c,escpofd,j}*cpop_{c,j}*CFofd_c*8760*PVA_{d_r,E}$$

$$[Cost\_of\_shortfall\_in\_failing\_to\_meet\_national\_RPS\_requirements]$$
$$+RPSSCost*RPS\_Shortfall$$

$$[Cost\_of\_shortfall\_in\_failing\_to\_meet\_state-level\_RPS\_requirements]$$
$$+\sum_{states}(ST\_RPSSCost_{states}*ST\_RPS\_Shortfall_{states})$$

$$[wind\_growth\_multiplier\_on\_wind\_capital\_\cos t]$$
$$+\sum_{g}CG_g*WCt_g$$

$$[wind\_installation\_growth\_multiplier\_on\_wind\_installation\_capital\_\cos t]$$
$$+\sum_{ginst}CGinst_{ginst}*WCtinst_{ginst}$$

$$[Conventional\_generators\_capital\_\cos t\_and\_fixed\_O\&M\_throughout\_the\_analysis\_period]$$
$$+\sum_{n,q}(CCONV_q + Cgridconnect + CCONVF_q)*CONVCAP_{n,q}$$
$$[Conventional\_generation\_\text{var}\,iable\_O\&M]$$
$$+\sum_{n,q}CCONVV_{n,q}*(CONVGEN_{m,n,q} + CONVPGEN_{mpeak,n,q}*PCOSTFRAC_q)$$
$$[Low\_sulfur\_coal\_incremental\_\cos t]$$
$$+\sum_{n}(coallowsulinc\cos t_n * cheatrate_{coal} * PVA_{coal,d_r,E,e})*coalowsul_n$$
$$[Spinning\_reserve\_operating\_and\_fuel\_\cos t]$$
$$+\sum_{m,n,q}CSRV_{n,q}*SR_{m,n,q}*H_m$$
$$[Quick\_start\_capacity\_\cos t]$$
$$+\sum_{n,q}CQS*QS_{n,q}$$
$$[Interruptible\_load\_capacity\_\cos t]$$
$$+\sum_{n}IL_n*CILA + \sum_{i\lg,n}CIL_{i\lg}*ILt_{i\lg,n}$$
$$[Grid\_transmission\_\text{var}\,iable\_\cos t]$$
$$+\sum_{m,n,p}H_m*CONVT_{m,n,p}*(TOCost*dis_{n,p} + POSTSTWCOST*PostStamp_{n,p})*PVA_{d_r,E}$$
$$[Grid\_transmission\_capital\_\cos t\_of\_new\_transmission\_lines]$$
$$+\sum_{n,p}TPCAN_{n,p}*TNCost*dis_{n,p}$$
$$[\Pr ice\_vs\_\cos t\_differential\_due\_to\_rapid\_growth]$$
$$+\sum_{tpca\_g}TPCA\_CG_{tpca\_g}*TPCA\_Ct_{tpca\_g}$$
$$[Carbon\_tax\_\cos t]$$
$$+carbtax\max * ctaxdiscsum * \sum_{m,n,q}CONVpol_{carbon,q}*H_m*(convgen_{m,n,q} + convp_{n,peak,q})*cheatrate_q$$

$$[Capital\_and\_fixed\_operating\_cost\_for\_storage\_conversion\_at\_a\_wind\_site]$$

$$+(CCH2_{electrolyzer}+CfixOMH_{electrolyzer}*PVA_{d_r,E})*\sum_{i}ELE_i$$

$$[Variable\_cost\_throughout\_the\_analysis\_period\_for\_storage\_conversion\_at\_a\_wind\_site]$$

$$+CAOMH_{electrolyzer}*(\sum_{i}hfs_i+\sum_{c,hscp,i}hf\_inregion_{c,hscp,i}+(\sum_{c,i,s}fcell\_inregion_{c,i,s}+\sum_{i,r,s}fcell_{i,r,s})/CHEFF_{fuelcell})$$

$$[Capital\_cost\_of\_storage\_at\_a\_wind\_site;\_storage\_sized\_for\_one\_summer\_day's\_throughout]$$

$$+CCH2_{storageatwind}*\sum_{i}h2stored\_summerday_i$$

$$[Storage\_at\_wind\_variable\_and\_fixed\_O\&M\_cost\_throughout\_the\_analysis\_period]$$

$$+(CAOMH_{storageatwind}+CfixOMH_{storageatwind}*PVA_{d_r,E})*(\sum_{c,i,s}fcell\_inregion_{c,i,s}+\sum_{i,r,s}fcell_{i,r,s})/CHEFF_{fuelcell}$$

$$[Cost\_to\_transport\_H2\_fuel\_from\_a\_wind\_farm\_to\_a\_city\_gate\_within\_the\_same\_region]$$

$$+\sum_{c,hscp,j}(hf\_inregion_{c,hscp,j}*hf\_inregion\_cost_{c,hscp,j})*PVA_{d_r,E}$$

$$[Capital\_cost\_and\_fixed\_operating\,cost\_of\_fuel\_cell\_at\_wind\_site]$$

$$+(CCH2_{fuelcell}+CfixOMH_{fuelcell}*PVA_{d_r,E}*\sum_{i}Fcellcapacity_i$$

$$[Variable\_O\&M\_cost\_throughout\_the\_analysis\_period\_of\_Fuel\_cell\_a\bar{t}\_wind\_site]$$

$$+CAOMH_{fuelcell}*(\sum_{c,i,s}fcell\_inregion_{c,i,s}+\sum_{i,r,s}fcell_{i,r,s})$$

$$[H2\_fuel\_transport\_variable\_and\_fixed\_O\&M\_cost\_throughout\_the\_analysis\_period\_$$
$$for\_H2\_from\_wind]$$

$$+(CAOMH_{h2transportation}*dis_{i,j}+CfixOMH_{h2transport}*PVA_{d_r,E})*\sum_{i,j}hf_{i,j}$$

$$[Cost\_adder\_for\_grid\_electricity\_supplied\_to\_electrolyzers\_at\_wind\_farms]$$

$$+\sum_{i,m}(grid\_2\_welectrolysis_{i,m}+grid\_2\_welectrolysis\_inregion_{i,m})*ind\_elec\_adder*PVA_{d_r,E}$$

$$[Distributed\_fuel\_cell\_capital\_cost\_and\_fixed\_O\&M]$$

$$+\sum_{n}DISFCELL\_CAP_n*(CCH2_{fuelcell}+CfixOMH_{fuelcell}*PVA_{d_r,E})$$

$$[Distributed\_fuel\_cell\_and\_storage\_variable\_O\&M\_cost]$$

$$+\sum_{j,m}hfdiselec\_2\_fcell_{j,m}*(CAOMH_{fuelcell}+CAOMH_{storageatcity})$$

$$[Storage\_at\_city\_capital\_cost\_and\_fixed\_O\&M]$$

$$+(\sum_{j,m}hfdiselec\_2\_fcell_{j,m}/summerdays)*(CCH2_{storageatcity}+CfixOMH_{storageatcity}*PVA_{d_r,E})$$

$$[Steam\_methane\_reformer\_capital\_\cos t\_plus\_fixed\_O\&M\_\cos t\_throughout\_the\_analysis\_period]$$
$$+(CCH2_{ngreformer}+CfixOMH_{ngreformer}*PVA_{d_r,E})*\sum_j HF\_STEAMREF\_CAP_j$$
$$[Steam\_methane\_reformer\_\text{var}iable\_O\&M\_\cos t\_and\_natural\_gas\_\cos t\_throughout\_the\_analysis\_period]$$
$$+\sum_j hfsteamref_j*(CAOMH_{ngreformer}+Fprice_{gascc}*PVA_{gas.j,d,E}/CHEFF_{ngreformer})$$

$$[Distributed\_electrolyzer\_capital\_\cos t\_and\_fixed\_O\&M\_\cos t\_throughout\_the\_analysis\_period]$$
$$+\sum_j HF\_DISELEC\_CAP_j*(CCH2_{distributedelectrolyzer}+CfixOMH_{distributedelectrolyzer}*PVA_{d_r,E})$$
$$[Distributed\_electrolyzer\_\text{var}iable\_O\&M\_\cos t\_and\_industrial\_electricity\_adder\_throughout\_the\_analysis\_period]]$$
$$+(\sum_j hfdiselec_j+\sum_{j,m} hfdiselec\_2\_fcell_{j,m})*(CAOMH_{distributedelectrolyzer}+ind\_elec\_adder/CHEFF_{distributedelectrolyzer}*PVA_{d_r,E})$$

$$[Value\_of\_hydrogen\_produced]$$
$$-H2PRICE*(\sum_{c,hscp,i} hf\_inregion_{c,hscp,i}+\sum_i hfd_i+\sum_i hfdiselec_i+\sum_i hfsteamref_i)*PVA_{d_r,E}$$
$$[carbon\_emissions\_\cos t]$$
$$+carbtax\max*ctaxdiscsum*steam\_ref\_emiss_{pol}*\sum hfsteamref_j/CHEFF_{ngreformer}$$

$$[Electrolyzer\_growth\_multiplier\_on\_electrolyzer\_capital\_\cos t]$$
$$+\sum_{hebp} CGelectrolyzer_{hebp}*HEGBIN_{hebp}$$
$$[Steam\_methane\_reformer\_growth\_multiplier\_on\_SMR\_capital\_\cos t]$$
$$+\sum_{hsmrbp} CGSMR_{hsmrbp}*HSMRGBIN_{hsmrbp}$$
$$[Fuel\_cell\_growth\_multiplier\_on\_fuel\_cell\_capital\_\cos t]$$
$$+\sum_{hfcbp} CGFC_{hfcbp}*HFCGBIN_{hfcbp}$$

Where:

E is the evaluation period (years) over which all investments are considered

CW_c is the capital cost of class c wind ($/MW) (see equation in Financial Parameters section)

$cslope_{c,i}$ is the average slope of the terrain at class c sites in region i

cslopeWcostfactor is the fractional increase in wind capital cost per degree of topographical slope

cslopeTcostfactor is the fractional increase in new transmission line capital cost per degree of topographical slope

$CWOM_c$ is the present value over the evaluation period (E) of the operating costs (variable and fixed) for a class c wind machine ($/MWh for E years) (see equation in Financial Parameters section)

$CWOMcofs_c$ is the present value of E years of fixed and variable operating costs for class c shallow offshore wind including production tax credits

$CWOMcofd_c$ is the present value of E years of fixed and variable operating costs for class c deep offshore wind including production tax credits

$class_{c,i}$ is the binary parameter that indicates whether class c onshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best onshore wind to consider in this time period

$classT_{c,i}$ is the binary parameter that indicates whether class c onshore wind in region i that uses new (installed in this time period) transmission is the best onshore wind to consider in this time period

$classofd_{c,i}$ is the binary parameter that indicates whether class c deep offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best deep offshore wind to consider in this time period

$classofs_{c,i}$ is the binary parameter that indicates whether class c shallow offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best shallow offshore wind to consider in this time period

$classTofd_{c,i}$ is the binary parameter that indicates whether class c deep offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period

$classTofs_{c,i}$ is the binary parameter that indicates whether class c shallow offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period

Cgridconnect is the cost of the substation and other expenses related to connecting to the grid, not including any transmission line builds ($/MW)

TOCost is the cost for wind to use existing transmission lines ($/MWh-mile)

TNCost is the cost of new transmission lines ($/MW-mile)

TNWCost is the cost to build a new transmission line ($/MW-mile)

TOWCost is the cost of wind transmission on existing lines ($/MWh-mile)

$WR2GPTSofd_{c,i,wscpofd}$ is the cost ($/MW) of building transmission interconnect to the grid for class c deep offshore wind resource in region i in supply curve step wscpofd

$WR2GPTSofs_{c,i,wscpofs}$ is the cost ($/MW) of building transmission interconnect to the grid for class c shallow offshore wind resource in region i in supply curve step wscpofs.

$dis_{i,j}$ is the distance between wind supply region i and demand region j (miles)
POSTSTWCOST is the cost to transmit into or across a PCA on existing transmission lines ($/MW-PCA)
$PostStamp_{i,j}$ is the number of PCAs that must be crossed to transmit from wind supply region i to demand region j
CF_c is the capacity factor for new onshore wind at a class c site
$CFcofd_c$ is the annual capacity factor of new deep offshore wind systems of class c in the time period being run
$CFcofs_c$ is the annual capacity factor of new shallow offshore wind systems of class c in the time period being run
$MW\_inregion\_dis_{c,escp,j}$ is the levelized cost from the escp step of the supply curve for the cost of building a transmission line within region i from a class c onshore wind site to a load center
$MW\_inregion\_disofd_{c,escpofd,j}$ is the levelized cost from the escpofd step of the supply curve for the cost of building a transmission line within region i from a class c deep offshore wind site to a load center
$MW\_inregion\_disofs_{c,escpofs,j}$ is the levelized cost from the escp step of the supply curve for the cost of building a transmission line within region i from a class c shallow offshore wind site to a load center
RPSSCost is the penalty imposed on utilities for not meeting the national RPS requirement
RPS_Shortfall is the variable for the additional amount of wind generation needed to meet the national RPS requirement beyond that supplied
$ST\_RPSSCost_{states}$ is the penalty imposed on utilities for not meeting the RPS requirement in "states"
$ST\_RPS\_Shortfall_{states}$ is the variable for the additional amount of wind generation needed to meet the RPS requirement beyond that supplied in "states"
$IWSurplus_{c,i,in}$ is the fraction of wind from a class c site in region i that is supplied to interconnect in that cannot be used because there is excess generation (see Wind Intermittency Parameters section)
$cpop_{c,i}$ is a multiplier on the capital cost of transmission lines for wind to account for increased siting/land costs in highly populated areas. The value varies between 1 and 2 as a linear function of population density in the vicinity of class c wind sites in region i.
$WR2GPTS_{c,i,wscp}$ is the cost to build transmission from the class c wind site in region i to the closest available grid transmission capacity ($/MW) (see Appendix D, GIS Calculations.)
$CCH2_{technology\ name}$ is the capital cost of the storage (hydrogen) technology ($/MW or $/unit stored energy)
$CAOMH_{technology\ name}$ is the present value over the evaluation period of the variable operating cost (including any production tax credit) of the storage (hydrogen) technology ($/MWh or $/unit stored energy)
$CfixOMH_{technology\ name}$ is the fixed operating cost of the storage (hydrogen) technology ($/MW-yr or $/unit stored energy)
$CHEFF_{technology\ name}$ is the efficiency of the storage (hydrogen) technology (units out/units in)

hf_inregion_cost$_{c,hscp,j}$ is the cost associated with step hscp for the shipment of hydrogen from a class c wind site within region i to a city within the region

ind_elec_adder is the additional cost beyond the wholesale cost for delivering grid electricity to distributed electrolyzers and electrolyzers at the wind site

h2stored_summerday$_i$ is storage (e.g., hydrogen storage) capacity required to meet the on-peak operation of the fuel cells at wind sites in region i

H2PRICE is the price that hydrogen will receive in the marketplace in this time period

H2energy is the annual production of energy for storage (e.g., hydrogen storage)

$$h2energy = (\sum_{s,i,r} fcell_{s,i,r} + \sum_{i,c,s} fcell\_inregion_{i,c,s}) / CHEFFfuelcell$$

H2energy_summerday is the energy produced for storage (e.g., hydrogen storage) during a summer day

$$h2energy\_summerday = (\sum_{i,r} fcell_{summer,i,r} + \sum_{i,c} fcell\_inregion_{i,c,summer}) /$$
$$CHEFFfuelcell / (numhourssummer / 24)$$

where **numhoursummer** is the number of hours in June – August

summerdays is the number of days in the summer (= numhoursummer/24)

carbtaxmax is the ultimate carbon tax level once the tax has been fully phased in ($/ton carbon)

ctaxdiscsum is the multiplier to convert annual cost of carbon to present value cost over the evaluation period

CGelectrolyzer$_{hebp}$ is the difference between the price and cost of the technology for converting power to stored energy in growth bin hebp ($/MW)

CGfuelcell$_{hfcbp}$ is the difference between the price and cost of the technology for converting stored energy to power in growth bin hfcbp ($/MW)

TPCA_CG$_{tpca_g}$ is the difference between the price and cost of transmission in transmission growth bin tpca_g ($/MW-mile) (see the Financial Parameters section)

CG$_g$ is the increase in turbine price over cost in growth bin g due to rapid growth in wind deployment ($/MW) (see the Financial Parameters section)

CGinst$_{ginst}$ is the increase in wind installation price over cost in growth bin ginst, due to rapid growth in wind deployment ($/MW) (see the Financial Parameters section)

H$_m$ is the number of hours in a year in time slice m

CCONV$_q$ is the present value of the revenue required to pay for the capital cost of one MWof capacity of generating technology q ($/MW) including interest during construction, finance and taxes (see the Financial Parameters section)

CCONVF$_q$ is the present value over the evaluation period of the fixed operating costs for conventional technology q ($/MW-yr) (see the Financial Parameters section)

CCONVV$_{n,q}$ is the present value over the evaluation period of the variable operating and fuel costs for conventional technology q in PCA n ($/MWh) (see the Financial Parameters section)

PCOSTFRAC$_q$ is the multiplier on the operating costs of technology q for use as a peaker (i.e. when the generation in the diurnal peak period exceeds the average generation in the diurnal shoulder periods)

coallowsulincost$_r$ additional cost of low-sulfur coal (relative to high-sulfur coal) ($/Mbtu)

Ecostescal$_{n,q}$ is the annual real price escalation of fuel used in PCA n by technology q

cur_year is the calendar year of the last year of the current 2-year period

$cheatrate_q$ is the heat rate for technology q (MBTU/MWh)

$PVA_{name,d,E,n}$ is the present value factor for fuel for technology q in PCA n escalating over time (see derivation in the Financial Parameters section)

$CONVpol(pollutant)_q$ is the emissions of pollutant (pounds per MWh)

Carboncost is the cost of carbon emissions ($/pound carbon)

$CCT_{n,p}$ is the present value over the evaluation period of the cost per MWh of transmission between PCAs n and p ($/MWh) (see the Financial Parameters section)

$CSRV_{n,q}$ is the present value over the evaluation period of the cost of spinning reserve in PCA n ($/MW-hour) of type q (see the Financial Parameters section)

CIL_n is the present value over the evaluation period of the base cost of interruptible load in PCA n ($/MWh)

CIL_{ilg} is the present value over the evaluation period of the cost of interruptible load in bin ilg ($/MWh), i.e. of higher levels of interruptible load use.

CQS is the cost to modify a generation plant for fast-start-capability to provide additional operating reserve ($/MW)

4. Constraints

The minimization of cost in WinDS is subject to a large number of different constraints, involving limits on wind resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, Constraint 1 below), these constraints apply to new wind turbines and storage (e.g., electrolyzers/hydrogen storage) facilities built in the time period being optimized.

After the constraint number, the constraint name is shown with the subscripts over which the constraint applies. For example, in Constraint 1 immediately below, the parenthetical (c,i) immediately following the name of the constraint implies that this constraint is applied for every class of onshore wind c and every region i. Because there are 358 regions i and five classes of wind c, this first type of constraint is repeated 1,790 times (358x5).

The constraints are listed in the order they occur in the model. Following the equation for the constraint, we define those constants and variables that are first introduced by this constraint.

<u>**Constraints On Wind**</u>

Constraint 1

WIND_RES_UC(c,i): For every wind class c and wind supply region i, the sum of all onshore wind capacity installed in this and preceding time periods must be less than the total onshore wind resource in the region (**$\mathbf{WRUC_{c,i}}$**)

$$\begin{aligned}
&\sum_{wscp} WturN_{i,wscp} * class_{c,i} + WturTN_i * classT_{c,i} \\
&+ Wtur_inregion_{c,i} + WturO_{c,i} + WTturO_{c,i} \\
&\leq WRUC_{c,i}
\end{aligned}$$

Where:

$\mathbf{WturO_{c,i}}$ is existing ("O"ld) (from the preceding time period) class c wind transmitted on existing transmission lines [MW] from region i
$\mathbf{WTturO_{c,i}}$ is existing class c wind transmitted on new transmission lines [MW] from region i

Constraint 2

WIND_RES_UC_ofs(c,i): For every wind class c and wind supply region i, the sum of all shallow offshore wind capacity installed in this and preceding time periods must be less than the total shallow offshore wind resource in the region (**$\mathbf{WRUCofs_{c,i}}$**)

$$\sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i} + WturTNofs_i * classTofs_{c,i}$$
$$+ Wtur\_inregionofs_{c,i} + WturOofs_{c,i} + WTturOofs_{c,i}$$
$$\leq WRUCofs_{c,i}$$

Where:

$WturOofs_{c,i}$ is existing (from the preceding time period) shallow offshore wind on existing transmission lines (MW)
$WTturOofs_{c,i}$ is existing shallow offshore wind on new transmission lines (MW)

Constraint 3
WIND_RES_UC_ofd(c,i): For every wind class c and wind supply region i, the sum of all deep offshore wind capacity installed in this and preceding time periods must be less than the total deep offshore wind resource in the region (**$WRUCofd_{c,i}$**)

$$\sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i} + WturTNofd_i * classTofd_{c,i}$$
$$+ Wtur\_inregionofd_{c,i} + WturOofd_{c,i} + WTturOofd_{c,i}$$
$$\leq WRUCofd_{c,i}$$

Where:

$WturOofd_{c,i}$ is existing (from the preceding time period) deep offshore wind on existing transmission lines (MW)
$WTturOofd_{c,i}$ is existing deep offshore wind on new transmission lines (MW)

The next three constraints ensure that the amount of wind that can access existing transmission is less than or equal to the amount of wind available in each step of the supply curve for the cost of connecting to the grid.

Constraint 4
WIND_supply_curves(c,i,wscp): New onshore wind of class c in region i at interconnection cost step wscp must be less than the remaining onshore wind resource in that cost step (**$WR2G_{c,i,wscp}$**)[6]

$$WturN_{i,wscp} * class_{c,i} \le WR2G_{c,i,wscp}$$

Constraint 5
WIND_supply_curves_ofs(c,i,wscpofs): New shallow offshore wind of class c in region i at inteconnection cost step wscpofs must be less than the remaining shallow offshore wind resource in that cost step (**$WR2Gofs_{c,i,wscpofs}$**)

$$WturNofs_{i,wscpofs} * classofs_{c,i} \le WR2Gofs_{c,i,wscpofs}$$

Constraint 6
WIND_supply_curves_ofd(c,i,wscpofd): New deep offshore wind of class c in region i at inteconnection cost step wscpofd must be less than the remaining deep offshore wind resource in that cost step (**$WR2Gofd_{c,i,wscpofd}$**)

$$WturNofd_{i,wscpofd} * classofd_{c,i} \le WR2Gofd_{c,i,wscpofd}$$

The next six constraints ensure that the new wind capacity on transmission lines from a region are less than the new turbine capacity built in the region

Constraint 7
Wind_2_Grid(c,i): The new class c onshore wind transmitted from a region i on existing lines to all regions j must be less than or equal to the total amount of new onshore region i class c wind used from the onshore class c wind supply curve for existing lines.

$$\sum_j WN_{i,j} * class_{c,i} \le \sum_{wscp} WturN_{i,wscp} * class_{c,i}$$

---

[6] Wind Transmission Pre-Calculation

A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind and deep offshore wind for each wind class c and region i. This supply curve is comprised of four quantity/cost pairs ($WR2G_{c,i,wscp}$ / $WR2GPTS_{c,i,wscp}$). The "curve" provides the amount of class c wind $WR2G_{c,i,wscp}$ of each type l (onshore, shallow offshore, and deep offshore) that can be connected to the existing grid for a cost between $WR2GPTS_{c,i,wscp-1}$ and $WR2GPTS_{c,i,wscp}$. This "pre-LP" optimization is described in more detail in Appendix B. The quantity $WR2G_{c,i,wscp}$ is reduced after each period's LP optimization by the amount of wind used in the time period from that cost step.

Constraint 8
Wind_2_Grid_OFS(c,i): The new class c shallow offshore wind transmitted from a region i on existing lines to all regions j must be less than or equal to the total amount of new shallow offshore region i class c wind used from the shallow offshore class c wind supply curve for existing lines.

$$\sum_{j} WNofs_{i,j} * classofs_{c,i} \leq \sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i}$$

Constraint 9
Wind_2_Grid_OFD(c,i): The new class c deep offshore wind transmitted from a region i on existing lines to all regions j must be less than or equal to the total amount of new deep offshore region i class c wind used from the deep offshore class c wind supply curve for existing lines.

$$\sum_{j} WNofd_{i,j} * classofd_{c,i} \leq \sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i}$$

Constraint 10
Wind_2_New(c,i): The new class c onshore wind transmitted from a region i on new lines to all regions j must be less than or equal to the total amount of new onshore region i wind used from the class c wind supply curve for new lines.

$$\sum_{j} WTN_{i,j} * classT_{c,i} \leq \sum_{wscp} WturTN_{i,wscp} * classT_{c,i}$$

Constraint 11
Wind_2_New_OFS(c,i): The new class c shallow offshore wind transmitted from region i on new lines to all regions j must be less than or equal to the total amount of new shallow offshore region i class c wind used from the shallow offshore class c wind supply curve for new lines.

$$\sum_{j} WTNofs_{i,j} * classTofs_{c,i} \leq \sum_{wscpofs} WturTNofs_{i,wscpofs} * classTofs_{c,i}$$

Constraint 12
Wind_2_New_OFD(c,i): The new class c deep offshore wind transmitted from a region i on new lines to all regions j must be less than or equal to the total amount of new deep offshore region i class c wind used from the deep offshore class c wind supply curve for new lines.

$$\sum_{j} WTNofd_{i,j} * classTofd_{c,i} \leq \sum_{wscpofd} WturTNofd_{i,wscpofd} * classTofd_{c,i}$$

Constraint 13
WIND_EXISTTRANS_BALANCE(i): Constraint to set the value of the amount of new wind on existing transmission lines taken from the onshore wind supply curve

The new wind from all steps on the supply curve must equal the sum of new wind sent from region i to all regions j. WNSC will be used in the objective function for the class of wind being considered this period in region i to determine the cost of reaching the grid.

$$\sum_{wscp} WNSC_{i,wscp} = \sum_{j} WN_{i,j}$$

Constraint 14
WIND_EXISTTRANS_BALANCE_ofs(i): Constraint to set the value of the amount of new wind on existing transmission lines taken from the shallow offshore wind supply curve

The new wind from all steps on the supply curve must equal the sum of new wind sent from region i to all regions j. WNSCofs will be used in the objective function for the class of wind being considered this period in region i to determine the cost of reaching the grid.

$$\sum_{wscpofs} WNSCofs_{i,wscpofs} = \sum_{j} WNofs_{i,j}$$

Constraint 15
WIND_EXISTTRANS_BALANCE_ofd(i): Constraint to set the value of the amount of new wind on existing transmission lines taken from the deep offshore wind supply curve

The new wind from all steps on the supply curve must equal the sum of new wind sent from region i to all regions j. WNSCofd will be used in the objective function for the class of wind being considered this period in region i to determine the cost of reaching the grid.

$$\sum_{wscpofd} WNSCofd_{i,wscpofd} = \sum_{j} WNofd_{i,j}$$

Constraint 16
RPSconstraint: This allows the model to include a national Renewable Portfolio Standard (RPS), wherein the total national annual wind generation must exceed a specified fraction of the national electricity load or a penalty must be paid on the shortfall (**RPS_Shortfall**).

$$
\begin{aligned}
&\sum_{\substack{c,i,j,m \\ I_i = I_j}} WN_{i,j} * class_{c,i} * CF_c * CF\_corr_{c,i,m} \\
&+ WNofs_{i,j} * classofs_{c,i} * CFofs_c * CF\_corrofs_{c,i,m} \\
&+ WNofd_{i,j} * classofd_{c,i} * CFofd_c * CF\_corrofd_{c,i,m} \\
&\\
&+ WTN_{i,j} * classT_{c,i} * CF_c * CF\_corr_{c,i,m} \\
&+ WTNofs_{i,j} * classTofs_{c,i} * CFofs_c * CF\_corrofs_{c,i,m} \\
&+ WTNofd_{i,j} * classTofd_{c,i} * CFofd_c * CF\_corrofd_{c,i,m} \\
&\\
&+ WO_{c,i,j} * CFO_{c,i} * CF\_corr_{c,i,m} \\
&+ WOofs_{c,i,j} * CFOofs_{c,i} * CF\_corrofs_{c,i,m} \\
&+ WOofd_{c,i,j} * CFOofd_{c,i} * CF\_corrofd_{c,i,m} \\
&\\
&+ WTO_{c,i,j} * CFTO_{c,i} * CF\_corr_{c,i,m} \\
&+ WTOofs_{c,i,j} * CFTOofs_{c,i} * CF\_corrofs_{c,i,m} \\
&+ WTOofd_{c,i,j} * CFTOofd_{c,i} * CF\_corrofd_{c,i,m} \\
&\\
&+ \sum_{c,escp,j} WELEC\_inregion_{c,escp,j} * CF_c * CF\_corr_{c,j,m} \\
&+ WELEC\_inregionofs_{c,escp,j} * CFofs_c * CF\_corrofs_{c,j,m} \\
&+ WELEC\_inregionofd_{c,escp,j} * CFofd_c * CF\_corrofd_{c,j,m} \\
&+ RPSPenalty \\
&\geq \\
&RPSFrac * \sum_{m,n} L_{m,n}
\end{aligned}
$$

Where:

$CFO_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c onshore wind on existing (at the start of the analysis time frame) lines in region i
$CFofs_c$ is the capacity factor for new shallow offshore wind at a class c site

$CFofd_c$ is the capacity factor for new deep offshore wind at a class c site
$CFOofd_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c deep offshore wind on existing (at the start of the analysis time frame) lines in region i
$CFOofs_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on existing (at the start of the analysis time frame) lines in region i
$WO_{c,i,j}$ is the existing (from the preceding time period) class c onshore wind on existing (at start of the simulation) transmission lines from region i to region j (MW)
$WOofd_{c,i,j}$ is the existing (from the preceding time period) class c deep offshore wind on existing (at start of the simulation) transmission lines from region i to region j (MW)
$WOofs_{c,i,j}$ is the existing (from the preceding time period) class c shallow offshore wind on existing (at start of the simulation) transmission lines from region i to region j (MW)
$WTO_{c,i,j}$ is the existing (at start of this time period) class c onshore wind on new transmission lines from region i to region j (MW)
$WTOofd_{c,i,j}$ is the existing (at start of this time period) class c deep offshore wind on new transmission lines from region i to region j (MW)
$WTOofs_{c,i,j}$ is the existing (at start of this time period) class c shallow offshore wind on new transmission lines from region i to region j (MW)

Constraints 17 and 18
WIND_GROWTH_TOT and WIND_GROWTH_BIN(G): These two constraints allocate new wind capacity (MW) to bins that have turbine costs associated with them over and above the turbine costs of the wind farms themselves. The bins are defined as a fraction of the national wind capacity (MW) at the start of the period

$$\begin{aligned}
&\sum_{c,i} Wtur_inregion_{c,i} + Wtur_inregionofs_{c,i} + Wtur_inregionofd_{c,i} \\
&+ \sum_{c,i}\sum_{wscp} WturN_{i,wscp} * class_{c,i} + \sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i} + \sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i} \\
&+ \sum_{c,i} WturTN_i * classT_{c,i} + WturTNofs_i * classTofs_{c,i} + WturTNofd_i * classTofd_{c,i} \\
&\le \sum_{g} WCt_g
\end{aligned}$$

$$WCt_g \le Gt_g * BASE\_WIND$$

Where:

Gt_g is a fractional multiplier of the national wind (MW) capacity
BASE_WIND is the national wind capacity (MW) at the start of the period

Constraints 19 and 20
WIND_GROWTH_INST(i) and WIND_GROWTH_BIN_INST(ginst,i): These two constraints allocate new wind capacity (MW) to bins that have costs associated with them over and above the installation cost of the wind farms themselves. The bins are defined as a fraction of the region

i wind capacity (MW) at the start of the period. These constraints capture the increase in installation prices with high growth in a single region. The first 200 MW don't count toward the installation cost increase.

$$
\begin{aligned}
&\sum_{c} Wtur\_inregion_{c,i} + Wtur\_inregionofs_{c,i} + Wtur\_inregionofd_{c,i} \\
&+ \sum_{c}\sum_{wscp} WturN_{i,wscp} * class_{c,i} + \sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i} + \sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i} \\
&+ \sum_{c,i} WturTN_{i} * classT_{c,i} + WturTNofs_{i} * classTofs_{c,i} + WturTNofd_{i} * classTofd_{c,i} \\
&- 200 \\
&\le \sum_{g} WCtinst_{ginst,i}
\end{aligned}
$$

$$WCtinst_{ginst,i} \le Gtinst_{ginst} * BASE\_WINDinst_{i}$$

Where:

$Gtinst_{ginst}$ is a fractional multiplier of the regional wind (MW) capacity
$BASE\_WINDinst_i$ is the region i wind capacity (MW) at the start of the period

Constraint 21
WIND_GROWTH_2000: This constraint ensures that the wind installed by 2000 is consistent with historical installations totaling 3,125 MW

$$
\begin{aligned}
&\sum_{c,i} Wtur\_inregion_{c,i} + Wtur\_inregionofs_{c,i} + Wtur\_inregionofd_{c,i} + \sum_{wscp} WturN_{i,wscp} * class_{c,i} + WturO_{c,i} \\
&\le 3125
\end{aligned}
$$

Constraint 22
WIND_GROWTH_2002: This constraint ensures that the wind installed by 2002 is consistent with historical installations totaling 4,500 MW

$$
\begin{aligned}
&\sum_{c,i} Wtur\_inregion_{c,i} + Wtur\_inregionofs_{c,i} + Wtur\_inregionofd_{c,i} + \sum_{wscp} WturN_{i,wscp} * class_{c,i} + WturO_{c,i} \\
&\le 4500
\end{aligned}
$$

Constraint 23
WIND_interregion_trans(j): Due to existing transmission capacity usage and other limitations, the amount of wind power able to be transported on existing lines is limited. This constraint limits the wind imports and exports on existing lines to some fraction (**a_j**) of the capacity **(TRj)** of the transmission lines crossing the boundaries of supply region j

$$\sum_{\substack{i \neq j \\ I_i = I_j \\ c}} WN_{i,j} * class_{c,i} + WO_{c,i,j} + WN_{i,j} * class_{c,j} + WO_{c,i,j}$$

$$+ \sum_{\substack{i \neq j \\ I_i = I_j \\ c}} WNofs_{i,j} * classofs_{c,i} + WOofs_{c,i,j} + WNofs_{i,j} * classofs_{c,j} + WOofs_{c,i,j}$$

$$+ \sum_{\substack{i \neq j \\ I_i = I_j \\ c}} WNofd_{i,j} * classofd_{c,i} + WOofd_{c,i,j} + WNofd_{i,j} * classofd_{c,j} + WOofd_{c,i,j}$$

$$\leq a_j * TR_j$$

Where:

a_j is the fraction of existing transmission lines available to wind

$TR_j = \sum_{k \in j} T_k$ is the sum of the capacity of all existing lines crossing the region boundary

Constraint 24

WIND_BALANCE_PCAS(n): This constraint is a transmission capacity balance that defines $\mathbf{WT_{n,p}}$, the transmission capacity needed to handle wind transmission between PCAs. This transmission capacity required for wind is combined with that required by conventional generation to identify bottlenecks between PCAs through Constraint 55. The left-hand side of the constraint is the sum of all wind generation transmitted into the PCA plus all that generated within the PCA. The right-hand side is the sum of all the wind generation consumed in the PCA plus all that transmitted from the PCA.

$$\sum_{\substack{n \prec p \\ I_n = I_p}} WT_{n,p} + \sum_{\substack{i \in n \\ I_i = I_j \\ c,j}} WN_{i,j} * class_{c,i} + WO_{c,i,j} + \sum_{\substack{i \in n \\ I_i = I_j \\ c,j}} WNofs_{i,j} * classofs_{c,i} + WOofs_{c,i,j} + \sum_{\substack{i \in n \\ I_i = I_j \\ c,j}} WNofd_{i,j} * classofd_{c,i} + WOofd_{c,i,j}$$

$$= \sum_{\substack{n \prec p \\ I_n = I_p}} WT_{n,p} + \sum_{\substack{j \in n \\ I_i = I_j \\ c,i}} WN_{i,j} * class_{c,i} + WO_{c,i,j} + \sum_{\substack{j \in n \\ I_i = I_j \\ c,i}} WNofs_{i,j} * classofs_{c,i} + WOofs_{c,i,j} + \sum_{\substack{j \in n \\ I_i = I_j \\ c,i}} WNofd_{i,j} * classofd_{c,i} + WOofd_{c,i,j}$$

Constraint 25

WIND_DEMAND_LIMIT(j,m): This constraint defines $\mathbf{WS_{j,m}}$ to be the maximum of zero and the difference between the wind-generated electricity consumed in region j in time slice m and all the electricity consumed in region j (i.e., $WS_{j,m}$ is non-zero only if the wind power consumed in region j is greater than the total demand in time slice m. This can occur in off-peak time slices if large amounts of wind are sent to region j to meet the demand in other time slices). $WS_{j,m}$ is then subtracted from the wind contribution to meeting the LOAD_PCA constraint for time slice m. In effect, these two constraints impose a penalty on excessive shipments of wind to an individual region j by not counting the wind power that exceeds the demand in any individual time slice. This precludes the model from shipping wind to a region near the wind production region and then shipping the wind generation out with conventional generation to other PCAs using conventional lines, i.e. without taking account of the fact that any transmission reserved for wind will only be used when the wind is blowing.

$$
\begin{aligned}
& WS_{j,m} \geq \\
& (\sum_{\substack{c,i \\ j \in n \\ I_i = I_j}} WN_{i,j} * class_{c,i} * CF_c * CF\_corr_{i,c,m} * (1 - IWSurplusMar_{c,i,in}) \\
& + WNofs_{i,j} * classofs_{c,i} * CFofs_c * CF\_corrofs_{c,i,m} * (1 - IWSurplusMar_{c,i,in}) \\
& + WNofd_{i,j} * classofd_{c,i} * CFofd_c * CF\_corrofd_{c,i,m} * (1 - IWSurplusMar_{c,i,in})) * (1 - TWLOSS * dis_{i,j}) \\
& \\
& + (\sum_{\substack{c,i \\ j \in n \\ I_i = I_j}} WTN_{i,j} * classT_{c,i} * CF_c * CF\_corr_{c,i,m} * (1 - IWSurplusMar_{c,i,in}) \\
& + WTNofs_{i,j} * classTofs_{c,i} * CFofs_c * CF\_corrofs_{c,i,m} * (1 - IWSurplusMar_{c,i,in}) \\
& + WTNofd_{i,j} * classTofd_{c,i} * CFofd_c * CF\_corrofd_{c,i,m} * (1 - IWSurplusMar_{c,i,in})) * (1 - TWLOSS * dis_{i,j}) \\
& \\
& + (\sum_{\substack{c,i \\ j \in n}} WO_{c,i,j} * CFO_{c,i} * CF\_corr_{c,i,m} * (1 - IWSurplusOld_{in}) \\
& + WOofs_{c,i,j} * CFOofs_{c,i} * CF\_corrofs_{c,i,m} * (1 - IWSurplusOld_{in}) \\
& + WOofd_{c,i,j} * CFOofd_{c,i} * CF\_corrofd_{c,i,m} * (1 - IWSurplusOld_{in})) * (1 - TWLOSS * dis_{i,j}) \\
& \\
& + (\sum_{\substack{c,i \\ j \in n}} WTO_{c,i,j} * CFTO_{c,i} * CF\_corr_{c,i,m} * (1 - IWSurplusOld_{in}) \\
& + WTOofs_{c,i,j} * CFTOofs_{c,i} * CF\_corrofs_{c,i,m} * (1 - IWSurplusOld_{in}) \\
& + WTOofd_{c,i,j} * CFTOofd_{c,i} * CF\_corrofd_{c,i,m} * (1 - IWSurplusOld_{in})) * (1 - TWLOSS * dis_{i,j}) \\
& \\
& + \sum_{\substack{C \\ j \in N}} \sum_{escp} WELEC\_inregion_{c,escp,j} * CF_c * CF\_corr_{c,j,m} * (1 - IWSurplusMar_{in}) \\
& + WELEC\_inregionofs_{c,escp,j} * CFofs_c * CF\_corrofs_{c,j,m} * (1 - IWSurplusMar_{in}) \\
& + WELEC\_inregionofd_{c,escp,j} * CFofd_c * CF\_corrofd_{c,j,m} * (1 - IWSurplusMar_{in}) \\
& \\
& - \mathrm{Re}\, gDmd_{j,m} * loadgrowth_{n \subset j}^{\;curyear - 2000} \\
& \\
& - (\sum_{j \in n} hfdiselec_j * H2\_loadprofile_m + hfdiselec\_2\_fcell_{j,m}) / H_m / CHEFF_{distributed\_electrolyzer} \\
& - \sum_{j \in n} hfdiselec\_2\_fcell_{j,m} * CHEFF_{storage\_at\_city} / H_m \\
& - (\sum_{j \in n} grid\_2\_welectrolysis_{j,m} + grid\_2\_welectrolysis\_inregion_{j,m} + old\_grid\_2\_welectrolysis_{j,m}) / H_m
\end{aligned}
$$

Where:

$CFTO_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c onshore wind on new (built in this period) lines in region i

$CFTOofd_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c deep offshore wind on new (built in this period) lines in region i

$CFTOofs_{c,i}$ is the average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on new (built in this period) lines in region i

$RegDmd_{j,m}$ is the electric load in each hour of time slice m in the year 2000 in region j

$loadgrowth_n$ is the annual rate of growth of load in the PCA n that contains region j

cur_year is the first year of the two-year period for which the optimization is being performed

Conventional Transmission Constraints

Constraint 26

CONV_TRAN_PCA(m,n,p): Ensures that there is sufficient transmission capacity between contiguous PCAs n and p within the same grid interconnect to transmit wind generation and conventional generation in each time slice m. Transmission capacity added this period is included in both directions p-to-n and n-to-p because transmission lines are bidirectional.

$$WT_{n,p} + convt_{m,n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

Where:

$TPCAO_{n,p}$ is the transmission capacity between n and p that existed at the start of this period

Constraint 27

CONTRACT_TRAN_PCA(m,n,p): Ensures that there is sufficient transmission capacity between contiguous PCAs n and p within the same grid interconnect to transmit wind generation and contracted conventional capacity. Transmission capacity added this period is included in both directions p-to-n and n-to-p because transmission lines are bidirectional.

$$WT_{n,p} + CONTRACTCAP_{n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

Constraints 28 and 29

TPCA_GROWTH_TOT and TPCA_GROWTH_BIN(TPCA_G): These two constraints allocate new transmission capacity (MW) to bins that have costs associated with them over and above the cost of the transmission lines themselves. The bins are defined as a fraction of the national transmission capacity at the start of the period.

$$\sum_{\substack{n,p \\ n \prec p \\ n \in I_p}} TPCAN_{n,p} * dis_{n,p} + \sum_{\substack{c,i,j \\ i \neq j}} (WTN_{i,j} * classT_{c,i} + WTNofs_{i,j} * classTofs_{c,i} + WTNofd_{i,j} * classTofd_{i,j}) * dis_{i,j}$$
$$\leq \sum_{TPCA\_G} TPCA\_Ct_{tpca\_g}$$

$$TPCA\_Ct_{tpca\_g} \leq TPCA\_Gt_{tpca\_g} * BASETPCA$$

Where:

$TPCA\_Gt_{tpca\_g}$ is a fractional multiplier of the national transmission (MW) capacity BASETPCA

Constraint 30
TPCA_GROWTH_2000: This constraint ensures that the transmission capacity added nationwide in 2000 is consistent with historical additions in 2000 of 2,585,158 MW-miles

$$\sum_{\substack{n,p \\ n \prec p \\ n \in I_p}} TPCAN_{n,p} * dis_{n,p} + \sum_{\substack{c,i,j \\ i \neq j}} WTN_{i,j} * classT_{c,i} * dis_{i,j}$$
$$\leq 2585158$$

Constraint 31
TPCA_GROWTH_2002: This constraint ensures that the transmission capacity added nationwide in 2002 is consistent with historical additions in 2002 of 2,070,715 MW-miles

$$\sum_{\substack{n,p \\ n \prec p \\ n \in I_p}} TPCAN_{n,p} * dis_{n,p} + \sum_{\substack{c,i,j \\ i \neq j}} WTN_{i,j} * classT_{c,i} * dis_{i,j}$$
$$\leq 2070715$$

Constraint 32
TPCA_GROWTH_2004: This constraint ensures that the transmission capacity added nationwide in 2004 is consistent with historical additions in 2004 of 2,766,900 MW-miles

$$\sum_{\substack{n,p \\ n \prec p \\ n \in I_p}} TPCAN_{n,p} * dis_{n,p} + \sum_{\substack{c,i,j \\ i \neq j}} WTN_{i,j} * classT_{c,i} * dis_{i,j}$$
$$\leq 2766900$$

System Constraints

Constraint 33

LOAD_PCA(m,n): This constraint ensures that the load (MW) in time period m in PCA n is met with imports from PCAs contiguous to PCA n ($CONVT_{m,n,p}$) decremented for transmission losses and generation from conventional sources and wind, also reduced by transmission line losses. The wind output is also decreased by the amount of surplus wind that blows when there is no use for it because loads are low. Output from fuel cells, either at a wind site or distributed within the grid, also contributes to meeting peak loads. Finally, any wind generation that exceeds the demand in the time slice is lost (this prevents wind from simply being shipped to the nearest contiguous region in excess of the demand for power in that region at that time).

The load is expressed in terms of MW that must be provided during each hour of the time slice m. The load is comprised of the direct load, Lmn, plus the power needed by the distributed electrolyzers/compressors and the grid power provided to the wind-sited electrolyzers.

$$\sum_{\substack{p \prec n \\ I_p = I_n}} CONVT_{m,n,p} * (1 - TLOSS * dis_{p,n}) + \sum_{q} CONVGEN_{m,n,q} + \sum_{\substack{q \in Btech \\ m' \in ptime}} CONVP_{m',n,q}$$

$$+ (\sum_{\substack{c,i \\ j \in n \\ I_i = I_j}} WN_{i,j} * class_{c,i} * CF_c * CF\_corr_{c,i\,m} * (1 - IWSurplusMar_{c,i,in})$$

$$+ WNofs_{i,j} * classofs_{c,i} * CFofs_c * CF\_corrofs_{c,i\,m} * (1 - IWSurplusMar_{c,i,in})$$

$$+ WNofd_{i,j} * classofd_{c,i} * CFofd_c * CF\_corrofd_{c,i,m} * (1 - IWSurplusMar_{c,i,in})) * (1 - TWLOSS * dis_{i,j})$$

$$+ (\sum_{\substack{c,i \\ j \in n \\ I_i = I_j}} WTN_{i,j} * classT_{c,i} * CF_c * CF\_corr_{c,i,m} * (1 - IWSurplusMar_{c,i,in})$$

$$+ WTNofs_{i,j} * classTofs_{c,i} * CFofs_c * CF\_corrofs_{c,i,m} * (1 - IWSurplusMar_{c,i,in})$$

$$+ WTNofd_{i,j} * classTofd_{c,i} * CFofd_c * CF\_corrofd_{c\,i,\,m} * (1 - IWSurplusMar_{c,i,in})) * (1 - TWLOSS * dis_{i,j})$$

$$+ (\sum_{\substack{c,i \\ j \in n}} WO_{c,i,j} * CFO_{c,i} * CF\_corr_{c\,i,\,m} * (1 - IWSurplusOld_{in})$$

$$+ WOofs_{c,i,j} * CFOofs_{c,i} * CF\_corrofs_{c\,i,\,m} * (1 - IWSurplusOld_{in})$$

$$+ WOofd_{c,i,j} * CFOofd_{c,i} * CF\_corrofd_{c\,i,\,m} * (1 - IWSurplusOld_{in})) * (1 - TWLOSS * dis_{i,j})$$

$$+ (\sum_{\substack{c,i \\ j \in n}} WTO_{c,i,j} * CFTO_{c,i} * CF\_corr_{c,i,m} * (1 - IWSurplusOld_{in})$$

$$+ WTOofs_{c,i,j} * CFTOofs_{c,i} * CF\_corrofs_{c,i,m} * (1 - IWSurplusOld_{in})$$

$$+ WTOofd_{c,i,j} * CFTOofd_{c,i} * CF\_corrofd_{c,i,m} * (1 - IWSurplusOld_{in})) * (1 - TWLOSS * dis_{i,j})$$

$$+ \sum_{\substack{C \\ j \in n}} \sum_{escp} WELEC\_inregion_{c,escp,j} * CF_c * CF\_corr_{c,j,m} * (1 - IWSurplusMar_{in})$$

$$+ WELEC\_inregionofs_{c,escp,j} * CFofs_c * CF\_corrofs_{c,j,m} * (1 - IWSurplusMar_{in})$$

$$+ WELEC\_inregionofd_{c,escp,j} * CFofd_c * CF\_corrofd_{c,j,m} * (1 - IWSurplusMar_{in})$$

$$+ (\sum_{s \subset m} fcelldest_{n,s} + fcelldestold_{n,s} + \sum_{\substack{c \\ j \in n}} fcell\_inregion_{c,j,s}) / H_m * ptime_m$$

$$+ \sum_{j \in n} \sum_{s \subset m} (\sum_{mm \in s} hfdiselec\_2\_fcell_{j,mm} * optime_{mm}) * ptime_m * CHEFF_{fuel-cell} / H_m$$

$$- \sum_{j \in n} WS_{j,m}$$

$$\geq L_{m,n} + \sum_{p|n} CONVT_{m,n,p}$$

$$+ (\sum_{j \in n} hfdiselec_j * H2\_loadprofile_m + hfdiselec\_2\_fcell_{j,m}) / H_m / CHEFF_{distributed\_electrolyzer}$$

$$+ \sum_{j \in n} hfdiselec\_2\_fcell_{j,m} * CHEFF_{storage\_at\_city} / H_m$$

$$+ (\sum_{j \in n} grid\_2\_welectrolysis_{j,m} + grid\_2\_welectrolysis\_inregion_{j,m} + old\_grid\_2\_welectrolysis_{j,m}) / H_m$$

Where:

TLOSS is the fraction of conventional power lost in each mile of transmission

$\mathbf{CF\_corr}_{c,i,m}$ is the correction to the annual capacity factor for class c onshore wind in region i and time slice m

$\mathbf{CF\_corrofs}_{c,i,m}$ is the correction to the annual capacity factor for class c shallow offshore wind in region i and time slice m

$\mathbf{CF\_corrofd}_{c,i,m}$ is the correction to the annual capacity factor for class c deep offshore wind in region i and time slice m

$\mathbf{IWSurplusMar}_{c,in,j}$ is the fraction of wind generation lost from the next unit of wind installed in region i because there is no remaining load to be met by the wind in interconnect in.

$\mathbf{IWSurplusOld}_{in}$ is the fraction of wind generation lost from all the wind installed to date in interconnect in because there is no remaining load to be met by the wind in interconnect in.

TWLOSS is the fraction of wind power lost in each mile of transmission

$\mathbf{fcelldestold}_{n,s}$ is the fuel cell output from wind-sited fuel cells built in previous periods that ship power to PCA n in season s

$\mathbf{ptime}_{m}$ is a binary constant equal to one when m is a peak load time slice, zero otherwise

$\mathbf{L}_{m,n}$ is the load (MW) in time slice m in PCA n

$\mathbf{H2\_loadprofile}_{m}$ is the fraction of annual hydrogen production from nonwind production technologies that occurs in time slice m

$\mathbf{old\_grid\_2\_welectrolysis}_{i,m}$ is the electricity from the grid in region i in time slice m consumed by wind-sited electrolyzers built in previous periods

Constraint 34

RES_MARG_NERC(r): Ensures that the conventional and wind capacity (MW) and generation from storage (e.g., fuel cell generation) from both distributed grid-powered and wind-sited generators (e.g., fuel cells) during the peak summer period is large enough to meet the peak load plus a reserve margin and any storage input (e.g., electrolysis) requirements. The wind-site fuel cell generation (MWh) is converted to capacity by dividing by CFc, but is constrained by the availability of transmission to a capacity value of 1-WCVmar (i.e., the combined capacity of the wind turbines and wind-sited fuel cells is one). The capacity value of distributed fuel cells is determined as the hydrogen input (kg) to the fuel cells during the summer peak time slice times the conversion efficiency (kg to MWh) divided by the number of hours of operation during the summer peak time slice. Peak-load requirements in NERC region r can also be met by contracting for capacity located in other NERC regions. The peak-load requirements are increased by the summer peak time slice grid input to electrolyzers either distributed at load sites or located at wind sites, divided by the number of hours in the summer peak time slice.

$$\sum_{\substack{q\\n\in r}} CONVCAP_{n,q} * CONVCAPC_q$$
$$+\sum_{\substack{c,i\\j\in r}} (WN_{i,j} * class_{c,i} + WNofs_{i,j} * classofs_{c,i} + WNofd_{i,j} * classofd_{c,i}$$
$$+ WTN_{i,j} * classT_{c,i} + WTNofs_{i,j} * classTofs_{c,i} + WTNofd_{i,j} * classTofd_{c,i}) * WCVMAR_{c,i,r} * (1 - TWLOSS * dis_{i,j})$$
$$+\sum_{\substack{c,i\in r\\escp}} (WELEC\_inregion_{c,escp,i} + WELEC\_inregionofs_{c,escp,i} + WELEC\_inregionofd_{c,escp,i}) * WCVMAR_{c,i,r}$$
$$+\sum_{\substack{c,i\\j\in r}} (WO_{c,i,j} + WTO_{c,i,j} + WOofs_{c,i,j} + WTOofs_{c,i,j} + WOofd_{c,i,j} + WTOofd_{c,i,j}) * WCVold_r * (1 - TWLOSS * dis_{i,j})$$
$$+\sum_{c,i} (1 - WCVmar_{c,i,r}) / (1 - CF_c) * classT_{c,i} * fcell_{i,r,s} / numpeakhoursbyseason_s$$
$$+\sum_{c,i\in r} (1 - WCVmar_{c,i,r}) / (1 - CF_c) * fcell\_inregion_{c,i,s} / numpeakhoursbyseason_s$$
$$+\sum_{j\in r} hfdiselec\_2\_fcell_{h3,j} * CHEFF_{fuel-cell} / numpeakhoursbyseason_s$$
$$+\sum_{n\in r} \sum_{\substack{p\prec n\\ i_p = I_n}} CONTRACTCAP_{n,p} * (1 - TLOSS * dis_{p,n}) - CONTRACTCAP_{n,p}$$
$$\geq \sum_{n\in r} P_n * (1 + NERCRm_r)$$
$$+\sum_{i\in r} (grid\_2\_welectrolysis_{h3,i} + grid\_2\_welectrolysis\_inregion_{h3,i} + old\_grid\_2\_welectrolysis_{h3,i}) / H_{h3}$$

Where:

$CONVCAPC_q$ is the effective load-carrying capability of conventional capacity type q
$WCVmar_{c,i,r}$ (wind capacity value – marginal) is the effective load-carrying capacity in NERC region r of one MW at a new wind farm at a class c site in region i. $WCVmar_{c,i,r}$ is derived in detail in the later section on Wind Intermittency Parameters.
$WCVold_r$ is the effective load-carrying capacity of all the wind capacity installed in previous periods whose generation is transmitted to NERC region r. $WCVold_r$ is derived in detail in the later section on Wind Intermittency Parameters.
$NERCRm_r$ is the reserve margin requirement in NERC region r
H3 designates the peak time slice in the summer season

Constraint 35
OPER_RES(m,r): Ensures that the interruptible load, spinning reserve, quick-start capacity, and fuel cell capacity are adequate to meet the normal operating reserve requirement and that imposed by wind. The summer output is used to define the fuel cell capacity under the assumption that the maximum annual fuel cell output in each NERC region occurs in the summer peak time slice.

$$\sum_{n \in r} IL_n + \sum sr_{n,m,q} + QS_{n,q} * F_q$$
$$+ \sum_{n \in r} \sum_{q \in qck} (fcelldest_{n,s} + fcelldestold_{n,s}) / (numpeakhoursbyseason_s * (1 - CF_{class4}))$$
$$+ \sum_{j \in r} \sum_{c} fcell\_inregion_{c,j,s} / (numpeakhoursbyseason_s * (1 - CF_c))$$
$$+ \sum_{j \in r} hfdiselec\_2\_fcell_{h3,j} * CHEFF_{fuel-cell} / numpeakhoursbyseason_s$$
$$+ \sum_{n \in r} \sum_{t \in FCretper} DISFCELL\_CAP\_OLD_{n,t}$$
$$\geq resconf\,\mathrm{int} * (NOR_r + \sum_{c,i} WORmar_{c,i,r}$$
$$* \sum_{\substack{j \in r \\ I_i = I_j}} WN_{i,j} * class_{c,i} + WNofs_{i,j} * classofs_{c,i} + WNofd_{i,j} * classofd_{c,i}$$
$$+ \sum_{\substack{j \in r \\ j \neq i}} WTN_{i,j} * classT_{c,i} + WTNofs_{i,j} * classTofs_{c,i} + WTNofd_{i,j} * classTofd_{c,i}$$
$$+ \sum_{\substack{c \\ j \in r}} WORmar_{c,j,r} *$$
$$\sum_{escp} WELEC\_inregion_{c,escp,j} + WELEC\_inregionofs_{c,escp,j} + WELEC\_inregionofd_{c,escp,j}$$
$$+ WORold_r * \sum_{\substack{c,i \\ j \in r}} WO_{c,i,j} + WOofs_{c,i,j} + WOofd_{c,i,j} + WTO_{c,i,j} + WTOofs_{c,i,j} + WTOofd_{c,i,j})$$

Where:

$\mathbf{F_q}$ is the forced outage rate for generation type q
FCretper is the period during which the older remaining (i.e. not yet retired) fuel cells were constructed
resconfint is the confidence interval multiplier applied to the operating reserve standard deviation to ensure a high probability that the operating reserve will be available
$\mathbf{NOR_r}$ is the normal operating reserve standard deviation in NERC region r
$\mathbf{WORmar_{c,i,r}}$ is the operating reserve requirement induced by the marginal addition of one MW of wind in region i that is consumed in NERC region r

WORold$_r$ is the operating reserve requirement induced by all wind installed in previous periods that contributes to NERC region r

Constraints 36 and 37
IL_PENETRATION_TOT and Interruptible_Load_BIN(ILG): These two constraints implement an interruptible power supply curve. The second constraint is actually implemented as an upper bound, not as a constraint

$$IL_n \leq \sum_{ILG} ILt_{ILG,n}$$

$$ILt_{ILG,n} \leq ILGt_{ILG} * PCAdmdPK_n * loadgrowth_n^{cur\_year-2000}$$

Where:

ILGt$_{ILG}$ is the fraction of peak demand in step ILG of the supply curve
PCAdmdPK$_n$ is the peak demand in PCA n in 2000

Conventional Generator Constraints

Constraint 38
SPIN_RES_CAP(m,n,q): ensures that the useful generation (CONV) from a conventional plant of type q comprises at least a minimum fraction (MINSR) of the total generation (CONV +SR) in time slice m in PCA n

$$CONVGEN_{m,n,q} \geq MINSR_q * (SR_{m,n,q} + CONVGEN_{m,n,q})$$

Where:

MINSR$_q$ is the fraction of each type of plant q that must be on line and loaded in order to serve as spinning reserve
SR$_{m,n,q}$ is the spinning reserve capacity from technology q during time period m in PCA n.

Constraint 39
CAP_FO_POa(m,n,q): Ensures that the capacity (MW) in PCA n of type q derated by the average forced outage rate for type q generators is adequate to meet the load, quick-start, and spinning reserve required in time slice m.

$$CONVGEN_{m,n,q} + CONVPGEN_{m,n,q} * btech_q + SR_{m,n,q} + QS_{n,q} \leq CONVCAP_{n,q} * (1 - fo_q)$$

Where:

$btech_q$ is a binary variable that is 1 if q is a base-load technology and 0 otherwise
fo_q is the forced outage rate for generator type q

Constraint 40
B_peak_12b(q-baseload technologies,m-peak time slices,n): To prevent unrealistic cycling, base-load plants are constrained in peak time slices to generate no more electricity than the average of that which is generated in the shoulder time slices.

$$CONVGEN_{m,n,q} \leq (CONVGEN_{m',n,q} + CONVGEN_{m'',n,q})/2$$

Where:

m is the peak time slice within each season (summer, winter, spring, and fall)
m' and **m''** are the shoulder time slices within each season (summer, winter, spring, and fall)

Constraint 41
HYDRO_ENERGY(n): Restricts the energy available from hydroelectric capacity to conform to the historical availability of water (He_n).

$$\sum_{m} CONVGEN_{hyd,m,n} * H_m \leq He_n$$

<u>**Environmental Constraints**</u>

Constraint 42
LOWSULCOAL(n,q): This constraint essentially adds all the coal used in the different time slices throughout the year into the variable **$coalowsul_q$.**

$$coalowsul_q \leq \sum_{\substack{m \\ q \in coaltech}} H_m * CONVGEN_{m,n,q} + \sum_{\substack{m \in ptime \\ q \in coaltcch}} H_m * CONVPGEN_{m,n,q}$$

Constraint 43
LOWSULCOAL_LIMIT(q,n): This constraint precludes any unscrubbed existing (before 2000) coal plant that has made the capital investment to use low-sulfur coal from switching back to high-sulfur coal in this time period. (This constraint implicitly presumes that any existing coal plants adapted for low-sulfur coal use will retire in the same proportions as those that have not been adapted. It also implicitly presumes that new coal plants capable of burning low-sulfur coal will be built in the same proportion.)

$$coalowsul_{n,q} \geq (lowsulcoalold_{n,q} / Coal\_old\_prev_{n,q}) * CONVCAP_{n,q}$$

Where:

$\mathbf{lowsulcoalold}_{n,q}$ is the amount of electricity (MWh) generated from low sulfur coal in PCA n by coal technology q in the previous 2-year time period.
$\mathbf{Coal\_old\_prev}_{n,q}$ is the capacity (MW) of coal-fired generation in PCA n of type q in the previous 2-year period.

Constraint 44
LOWSULCOAL_LIMIT2(n,q): This constraint prevents the fraction of low-sulfur coal used in all existing coal generators from decreasing from the level used in the previous period. The constraint is needed because coal plants can switch from unscrubbed (coal-old-1) to scrubbed (coal-old-2) coal plants.

$$
\begin{aligned}
& coalowsul_{coal-old-1,n} + coalowsul_{coal-old-2,n} \\
& \geq ((lowsulcoalold_{coal-old-1,n} + lowsulcoalold_{coal-old-2,n}) \\
& /(Coal-old-prev_{coal-old-1,n} + Coal-old-prev_{coal-old-2,n}) \\
& *(CONVCAP_{coal-old-1,n} + CONVCAP_{coal-old-2,n})
\end{aligned}
$$

Where:

$\mathbf{coalowsul}_{coal\text{-}old\text{-}1,n}$ is the total conventional generation from coal-fired generation with scrubbers that existed before the analysis time frame in PCA n using low-sulfur coal
$\mathbf{coalowsul}_{coal\text{-}old\text{-}2,n}$ is the total conventional generation from coal-fired generation without scrubbers that existed before the analysis time frame in PCA n using low-sulfur coal
$\mathbf{Coal\_old\_prev}_{coal\text{-}old\text{-}1,n}$ is the capacity of coal-fired generation with scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous 2-year period.
$\mathbf{Coal\_old\_prev}_{coal\text{-}old\text{-}2,n}$ is the capacity of coal-fired generation without scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous 2-year period.

Constraint 45
SCRUBBER(n): The combined capacity of the scrubbed and unscrubbed coal plants must be greater than the total of the two from the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease.

$$
\begin{aligned}
& CONVCAP_{coal-old-1,n} + CONVCAP_{coal-old-2,n} \\
& \geq CONVOLD_{n,coal-old-1} - CONVRET_{n,coal-old-1} \\
& + CONVOLD_{n,coal-old-2} - CONVRET_{n,coal-old-2}
\end{aligned}
$$

Where:

$CONVRET_{n,q}$ is the capacity in PCA n of generation type q retired in this period. See the later section on retirements of conventional capacity.

Constraint 46

EMISSIONS(pol): Ensures that the national annual emission of each pollutant (CO_2, SO_2, Nox, Hg) by all generators and hydrogen production technologies is lower than a national cap (LP)

$$\begin{aligned}
&\sum_{n}\sum_{q,m} CONVGEN_{m,n,q} * H_m * CONVpol_{pol,q} * cheatrate_q \\
&+\sum_{n}\sum_{\substack{q\in btech\\ m\in ptime}} CONVPGEN_{m,n,q} * H_m * CONVpol_{pol,q} * cheatrate_q \\
&-coallowsulpolred * \sum_{n}\sum_{\substack{q\in coaltech\\ pol\in SO2pol}} CONVpol_{pol,q} * cheatrate_q * coalowsul_{n,q} \\
&+\sum_{j} hfsteamref_j * steam_ref_emiss_{pol} / CHEFF_{NG_reformer} \\
&\le LP_{pol}
\end{aligned}$$

Where:

$CONVpol_{pol,q}$ is the emission of pollutant pol (tons) from a million Btu of fuel consumed by generator type q
coallowsulpolred is the delta (tons) in SO_2 emissions per MWh between high sulfur and low sulfur coal
$steam\_ref\_emiss_{pol}$ is the emissions (tons) of pollutant pol per MMBtu of input gas to steam methane reforming
LP_{pol} is the national annual cap on pollutant pol (tons/year).

Storage Constraints (constraints on hydrogen production from wind)

Constraint 47

ELEC_and_H2_inregion(c,i,s): Constrains the hydrogen produced (i.e. stored wind energy) and the electricity generated for use within region i in season s to be less than or equal to the seasonal output from new onshore turbines in the region.

$$\begin{aligned}
&\sum_{escp} WELEC_inregion_{c,escp,i} * CF_c * CF_corrs_{c,i,s} * numhoursbyseason_s \\
&+ wind_2_electrolysis_inregion_{c,i,s} \\
&\le Wtur_inregion_{c,i} * CF_c * CF_corrs_{c,i,s} * numhoursbyseason_s
\end{aligned}$$

Where:

$CF\_corrs_{c,i,s}$ is a correction factor to the capacity factor to account for variations in the output of wind with a season compared to the annual average capacity factor CF_c.
$numhoursbyseason_s$ is the number of hours in season s

Constraint 48
ELECTROLYSIS_INPUT_INREGION(i,s): Ensures that the wind-generated electricity designated for input to the storage-conversion process (e.g., electrolyzers/hydrogen storage) within region i is greater than or equal to the energy needed to produce the stored energy (e.g., hydrogen) for transport fuel or on-peak electricity production within region i as well as the electricity required to operate the storage/compression. The ratio, $numhoursbyseason_s/8760$, at the end of the constraint apportions the stored energy (e.g., hydrogen) produced throughout the year to the season s.

$$
\begin{aligned}
&\sum_c wind\_2\_electrolysis\_inregion_{c,i,s} + \sum_{m \in s} grid\_2\_welectrolysis\_inregion_{i,m} \\
&\geq \sum_c fcell\_inregion_{c,i,s} / CHEFF_{fuel-cell} * (1/CHEFF_{electrolyzer} + CHEFF_{storage-at-wind}) \\
&+ \sum_{c,hscp} hf\_inregion_{c,hscp,i} / CHEFF_{electrolyzer} * (numhoursbyseason_s / 8760)
\end{aligned}
$$

Constraint 49
ELECandH2_FROM_WIND(c,i,s): Ensures that the new electricity to the grid and the wind-generated electricity to the new wind-sited electrolyzers are less than or equal to the output from the new class c wind turbines in region i in season s.

$$
\begin{aligned}
&(\sum_j WN_{i,j} * class_{c,i} * CF_c * CF\_corrs_{c,i,s} + \sum_j WTN_{i,j} * classT_{c,i} * CF_c * CF\_corrs_{c,i,s} \\
&\sum_j WNofs_{i,j} * classofs_{c,i} * CFcofs_c * CF\_corrsofs_{c,i,s} + \sum_j WTNofs_{i,j} * classTofs_{c,i} * CFcofs_c * CF\_corrsofs_{c,i,s} \\
&\sum_j WNofd_{i,j} * classofd_{c,i} * CFcofd_c * CF\_corrsofd_{c,i,s} + \sum_j WTNofd_{i,j} * classTofd_{c,i} * CFcofd_c * CF\_corrsofd_{c,i,s}) \\
&* numhoursbyseason_s + wind\_2\_electrolysis_{c,i,s} \\
&\leq numhoursbyseason_s * (\\
&CFc_c * CF\_corrs_{c,i,s} * (\sum_{wscp} WturN_{i,wscp} * class_{c,i} * CF\_corrs_{c,i,s} + WturTN_i * classT_{c,i}) \\
&+ CFcofs_c * CF\_corrsofs_{c,i,s} * (\sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i} * CF\_corrsofs_{c,i,s} + WturTNofs_i * classTofs_{c,i}) \\
&+ CFcofd_c * CF\_corrsofd_{c,i,s} * (\sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i} * CF\_corrsofd_{c,i,s} + WturTNofd_i * classTofd_{c,i}))
\end{aligned}
$$

Where:

$CF\_corrsofs_{c,i,s}$ is a seasonal adjustment to the capacity factor for new shallow offshore class c wind in region i
$CF\_corrsofd_{c,i,s}$ is a seasonal adjustment to the capacity factor for new deep offshore class c wind in region i

Constraint 50
ELECTROLYSIS_INPUT(i,s): Ensures that the electricity input to the storage conversion process (e.g., electrolyzer) is greater than or equal to the energy needed to produce the stored energy (e.g., hydrogen) for subsequent on-peak electricity production, and for transport fuel and compression or liquefaction of that fuel before transport.

$$\begin{aligned}&\sum_{c} wind\_2\_electrolysis_{c,i,s} + \sum_{m \in s} grid\_2\_welectrolysis_{i,m}\\&\geq \sum_{r} fcell_{i,r,s} / CHEFF_{fuel-cell} * (1/CHEFF_{electrolyzer} + CHEFF_{storage-at-wind})\\&+ hfs_{i}(1/CHEFF_{electrolyzer} + CHEFF_{h2-transportation}) * (numhoursbyseason_{s} / 8760)\end{aligned}$$

Where:

$CHEFF_{h2\text{-}transportation}$ is the electricity (MWh/kg) required to compress or liquefy the hydrogen before transporting it between regions.

Constraint 51
TRANSMIT_2_ELECTROLYZER(i,m): Ensures that the grid electricity used in the wind-sited electrolyzer can be transmitted on the transmission lines built to the wind site.

$$\begin{aligned}&grid\_2\_welectrolysis_{i,m} / h_{m}\\&\leq \sum_{j} WN_{i,j} * class_{c,i} + \sum_{j} WTN_{i,j} * classt_{c,i}\\&+ \sum_{j} WNofs_{i,j} * classofs_{c,i} + \sum_{j} WTNofs_{i,j} * classtofs_{c,i}\\&+ \sum_{j} WNofd_{i,j} * classofd_{c,i} + \sum_{j} WTNofd_{i,j} * classtofd_{c,i}\end{aligned}$$

Constraint 51a
TRANSMIT_2_ELECTROLYZER_INREGION(i,m): Ensures that the grid electricity used in the wind-sited electrolyzer can be transmitted on the transmission lines built from the load center in the same region to the wind site.

$$grid\_2\_welectrolysis\_inregion_{i,m} / h_m \leq \sum_{c,escp} WELEC\_inregion_{c,escp,i}$$

Constraint 52

GRID_LIMIT(i,s): This ensures that the grid power will only fill in behind wind in operating the electrolyzers. If it does more, it needs to be added to the electrolyzer capacity (which is computed as the difference between turbines and wind to grid). It's critical to separate out seasons, otherwise it will use all grid power in a single season's peak. Dividing by CF yields total capacity; multiplying by 1-CF yields the amount that can be filled in by grid electricity.

$$\sum_{m \in s} grid\_2\_welectrolysis_{i,m} + grid\_2\_welectrolysis\_inregion_{i,m}$$
$$\leq \sum_{c} (wind\_2\_electrolysis_{c,i,s} + wind\_2\_electrolysis\_inregion_{c,i,s})$$
$$* (1 - CF_c * CF\_corrs_{c,i,s}) / (CF_c * CF\_corrs_{c,i,s})$$

Constraint 53

ELECTROLYZER_CAPACITY(i): Defines electrolyzer capacity (MW) as the difference between wind turbine capacity and the capacity of the wind used for power generation (as opposed to the wind capacity used for hydrogen production). Another way to think about this is that the electrolyzer capacity is assumed to be the difference between the wind turbine capacity and the capacity of the transmission lines available to move the wind generated electricity to load.

$$ELE_i \geq \sum_{c}$$
$$(\sum_{wscp} WturN_{i,wscp} * class_{c,i} + WturTN_{c,i} * classT_{c,i} + Wtur\_inregion_{c,i}$$
$$+ \sum_{wscpofs} WturNofs_{i,wscpofs} * classofs_{c,i} + WturTNofs_{c,i} * classTofs_{c,i}$$
$$+ \sum_{wscpofd} WturNofd_{i,wscpofd} * classofd_{c,i} + WturTNofd_{c,i} * classTofd_{c,i})$$
$$-$$
$$(\sum_{j} WN_{i,j} * class_{c,i} + \sum_{j} WTN_{i,j} * classT_{c,i} + \sum_{escp} WELEC\_inregion_{c,escp,i}$$
$$+ \sum_{j} WNofs_{i,j} * classofs_{c,i} + \sum_{j} WTNofs_{i,j} * classTofs_{c,i}$$
$$+ \sum_{j} WNofd_{i,j} * classofd_{c,i} + \sum_{j} WTNofd_{i,j} * classTofd_{c,i})$$

Constraint 54
FUEL_CELL_PEAK_OUT(i,r,s): Ensures that peak fuel cell output (MWh) from a wind site fits on the transmission line leaving supply region i for NERC region r along with the direct wind electricity (MWh).

$$fcell_{s,i,r} \leq numpeakhoursbyseason_s *$$
$$(\sum_c (1 - CF_c * CF\_corrps_{c,i,s}) * \sum_{n \in r} (\sum_{\substack{j \in n \\ j \in I_i}} WN_{i,j} * class_{c,i} + \sum_{\substack{j \in n \\ j \neq i}} WTN_{i,j} * classT_{c,i})$$
$$+ \sum_c (1 - CFofs_c * CF\_corrpsofs_{c,i,s}) * \sum_{n \in r} (\sum_{\substack{j \in n \\ j \in I_i}} WNofs_{i,j} * classofs_{c,i} + \sum_{\substack{j \in n \\ j \neq i}} WTNofs_{i,j} * classTofs_{c,i})$$
$$+ \sum_c (1 - CFofd_c * CF\_corrpsofd_{c,i,s}) * \sum_{n \in r} (\sum_{\substack{j \in n \\ j \in I_i}} WNofd_{i,j} * classofd_{c,i} + \sum_{\substack{j \in n \\ j \neq i}} WTNofd_{i,j} * classTofd_{c,i}))$$

Where:

$CF\_corrps_{c,i,s}$ is the correction to the annual capacity factor for class c onshore wind in region i for the peak time slice in each season s
$CF\_corrpsofs_{c,i,s}$ is the correction to the annual capacity factor for class c shallow offshore wind in region i for the peak time slice in each season s
$CF\_corrpsofd_{c,i,s}$ is the correction to the annual capacity factor for class c deep offshore wind in region i for the peak time slice in each season s

Constraint 55
FUEL_CELL_PEAK_IN(n,s): Ensures that the peak fuel cell output (MWh) entering a PCA from a wind-sited fuel cell fits on the transmission line entering that PCA from the same wind site.

$$fcelldest(n,s) \leq numpeakhoursbyseasons * \sum_{\substack{i \\ j \in n}}$$
$$(\sum_c (1 - CF_c * CF\_corrps_{c,i,s}) * (WN_{i,j} * class_{c,i} + WTN_{i,j} * classT_{c,i})$$
$$+ \sum_c (1 - CFofs_c * CF\_corrpsofs_{c,i,s}) * (WNofs_{i,j} * classofs_{c,i} + WTNofs_{i,j} * classTofs_{c,i})$$
$$+ \sum_c (1 - CFofd_c * CF\_corrpsofd_{c,i,s}) * (WNofd_{i,j} * classofd_{c,i} + WTNofd_{i,j} * classTofd_{c,i}))$$

Constraint 56
FUEL_CELL_PEAK_INREGION(c,i,s): Ensures that peak fuel cell output (MWh) from a wind site fits on the transmission line leaving the wind site along with the direct wind electricity (MWh) to be used in the same region.

$$fcell\_inregion_{c,i,s} \le numpeakhoursbyseason_s *$$
$$((1 - CF_c * CF\_corrps_{c,i,s}) * \sum_{escp} WELEC\_inregion_{c,escp,i}$$
$$+ (1 - CFofs_c * CF\_corrpsofs_{c,i,s}) * \sum_{escp} WELEC\_inregionofs_{c,escp,i}$$
$$+ (1 - CFofd_c * CF - \_corrpsofd_{c,i,s}) * \sum_{escp} WELEC\_inregionofd_{c,escp,i})$$

Constraint 57

FUEL_CELL_BALANCE(r,s): Sets the fuel cell output (MWh) from wind supply regions going to NERC region r equal to the fuel cell input (MWh) to the NERC region in each season. It doesn't have to be done for each time slice, because such transfers are allowed only during peak time slices of each season. This is done to reduce the number of variables associated with the fuel cells

$$\sum_i fcell_{i,r,s} = \sum_{n \in r} fcelldest_{n,s}$$

Constraint 58

FUEL_CELL_CAPACITY_LOW(i,s): Sets a lower bound on the fuel cell capacity needed by translating the fuel cell generation into a capacity estimate. Because it doesn't know whether the new wind capacity at the wind farms where the fuel cell is located is on new or existing transmission lines, to be conservative, it uses the higher (because lower-class wind may be competitive with higher-class wind that must also pay for transmission capacity) capacity factor of new wind on new transmission lines (conservatively leaves less room for the fuel cell output).

$$Fcellcapacity_i \ge \sum_r fcell_{i,r,s} / (numpeakhoursbyseason_s * (1 - \sum_c CF_c * classT_{c,i}))$$
$$+ \sum_c fcell\_inregion_{c,i,s} / (numpeakhoursbyseason_s * (1 - CF_c))$$

The next 12 constraints increase the price of hydrogen and wind technologies over their costs to reflect rapid growth constraints.

Constraints 59 and 60

ELECTROLYZER_GROWTH_TOT and ELECTROLYZER_GROWTH_BIN(hebp): These two constraints allocate new electrolyzer capacity (both distributed and wind-sited) (MW) to bins that have costs associated with them over and above the direct cost of the electrolyzers themselves. The bins are defined as a fraction of the national electrolyzer capacity (MW) at the start of the period

$$\sum_{j} HF\_DISELEC\_CAP_j + ELE_j \le \sum_{hebp} HEGBIN_{hebp}$$
$$HEGBIN_{hebp} \le HEGBINCAP_{hebp} * BASE\_ELEC$$

Where:

HEGBINCAP$_{hebp}$ is a fractional multiplier of the national electrolyzer capacity
BASE_ELEC is the national electrolyzer capacity (MW) at the start of the period

Constraints 61 and 62
SMR_GROWTH_TOT and SMR_GROWTH_BIN(hsmrbp): These two constraints allocate new SMR capacity (kg/year) to bins that have costs associated with them over and above the direct cost of the SMR themselves. The bins are defined as a fraction of the national SMR capacity (kg/year) at the start of the period

$$\sum_{j} HF\_STEAMREF\_CAP_j \le \sum_{hsmrbp} HSMRGBIN_{hsmrbp}$$
$$HSMRGBIN_{hsmrbp} \le HSMRGBINCAP_{hsmrbp} * BASE\_SMR$$

Where:

HSMRGBIN$_{hsmrbp}$ is a variable for new national steam methane reformer capacity in growth bin hsmrbp
HSMRGBINCAP$_{hsmrbp}$ is a fractional multiplier of the national SMR capacity
BASE_SMR is the national SMR capacity (kg/year) at the start of the period

Constraints 63 and 64
FUELCELL_GROWTH_TOT and FUELCELL_GROWTH_BIN(hfcbp): These two constraints allocate new fuel cell capacity (both distributed and wind-sited) (MW) to bins that have costs associated with them over and above the direct cost of the fuel cells themselves. The bins are defined as a fraction of the national fuel cell capacity (MW) at the start of the period

$$\sum_{j} Fcellcapacity_j + \sum_{n} DISFCELL\_CAP_n \le \sum_{hfcbp} HFCGBIN_{hfcbp}$$
$$HFCGBIN_{hfcbp} \le HFCGBINCAP_{hfcbp} * BASE\_FCELL$$

Where:

HFCGBINCAP$_{hfcbp}$ is a fractional multiplier of the national fuel cell capacity
BASE_FCELL is the national fuel cell capacity (MW) at the start of the period

Hydrogen Fuel Constraints

Constraint 65

H2FUEL_MARKET_BALANCE(j): Ensures that the hydrogen fuel shipped into a region and the fuel supplied by the region is balanced by the fuel consumed in the region and the fuel shipped out of the region.

$$\sum_{i \prec j} hf_{i,j} + hfs_j = \sum_{i \prec j} hf_{j,i} + hfd_j$$

where the symbol $\prec$ indicates contiguity

Constraint 66

H2FUEL_INTER_REGION(j): Ensures that hfs is not used in region; because, if it were, the transport distance would be zero and therefore the cost of transport would be zero. In-region use can occur through the inregion variable with the cost of transport taken from the supply curve for inregion use.

$$hfs_j \le \sum_{i \prec j} hf_{j,i}$$

Constraint 67

HF_DEMAND(j): Ensures the intraregion transport of hydrogen fuel is accounted for. Demand can be met by wind-sited electrolyzers, distributed electrolyzers, or natural gas steam methane reformers – hfdold includes all wind-generated H2, but not H2 from diselec or steam reforming as these vary each period. Includes demand escalation over time.

$$\sum_{c,hscp} hf\_inregion_{c,hscp,j} + hfd_j + hfdiselec_j + hfsteamref_j$$
$$\le hfdemand_j * hfdemand\_escal^{ordyear} - hfdold_j$$

Where:

hfdemand$_j$ is the maximum annual demand for hydrogen as a transportation fuel for light-duty vehicles in region j in the base year
hfdemand_escal is the annual escalation in the demand for light-duty vehicle fuels.
ordyear is the year of the optimization minus 2000 (i.e., the number of years of demand growth)
hfdold$_j$ is the hydrogen transportation fuel supplied by all remaining hydrogen production facilities built in prior periods

Constraint 68

HF_STEAMREF(j): Ensures that the hydrogen (kg) produced by steam methane reformers (SMR) is less than the capacity (kg per year) of the steam methane reformers built in this period and those built in previous period that are not yet retired.

$$hfsteamref_j \le (HF\_STEAMREF\_CAP_j + \sum_{t \ge SMRretper} HF\_STEAMREF\_CAPOLD_{j,t}) * H2\_prodnhours / 8760$$

Where:

SMRretper is the period during which the older remaining (i.e. not yet retired) SMR were constructed
Hf_steamref_capold$_{j,t}$ is the SMR capacity (kg/year) built in region j in period t
H2_prodnhours is the number of hours that the conventional hydrogen production is operated each year

Constraint 69
HF_DISELEC(j): Ensures that the hydrogen produced by distributed electrolyzers (not sited at wind farms) is less than the capacity (MW) of distributed electrolyzers built in this period and those not yet retired.

$$hfdiselec_j + \sum_m hfdiselec\_2\_fcell_{j,m}$$
$$\le (HF\_DISELEC\_CAP_j + \sum_{t \ge DEretper} HF\_DISELEC\_CAPOLD_{j,t}) * h2\_prodnhours * CHEFF_{distributed-electrolyzer}$$

Where:

DEretper is the period during which the older remaining (i.e. not yet retired) distributed electrolyzers were constructed
HF_DISELEC_CAPOLD$_{j,t}$ is the distributed electrolyzer capacity built in region j in period t

5. Wind intermittency parameters

There are three basic intermittency parameters for wind that are calculated for each period in WinDS before the linear program optimization is conducted for that period. These include wind capacity value (WCV), wind operating reserve (WOR), and wind surplus (WSurplus). For each, a marginal value is calculated, which applies to new wind installed in the period, and an "old" value is calculated, which applies to all the wind built in previous periods. This section describes the statistical assumptions and methods used to calculate these values.

Wind Capacity Value
This is the capacity credit given to the wind contribution to meeting the reserve margin constraint in each NERC region. It is a function of the amount of wind consumed in the NERC region, the dispersion of the wind farms contributing that wind, the electric load in the NERC region, and the amount and reliability of conventional capacity contributing to the load in the NERC region. Generally, as more wind is used by the NERC region, the wind capacity value decreases.

For each additional MW of class c wind added in region i that is consumed in NERC region r, the capacity credit, $WCVmar_{c,i,r}$, is the amount of load that can be added in every hour without changing the loss of load probability in NERC region r. To calculate $WCVmar_{c,i,r,}$ we assume that for each hour in the period for which WCVmar is being evaluated, the sum of all the conventional generation consumed in the NERC region r, plus all the wind generation from all classes of existing wind consumed in the NERC region r, minus the load in the NERC region r is a random variable that can be well approximated by a normal probability distribution. This approximation improves in accord with the central limit theorem as the number of contributing conventional plants and wind farms increases. Let X be this random variable. Then

$$\mu_x = \mu_C + \mu_W - \mu_L$$

Where:

- **μ** denotes expected value
- **C** is generation from all conventional power plants that deliver power to NERC region r
- **W** is generation from all wind farms that deliver power to NERC region r
- **L** is the load in NERC region r

And since C, W, and L are statistically independent

$$\sigma^2_X = \sigma^2_C + \sigma^2_W + \sigma^2_L$$
$$\sigma_X = (\sigma^2_C + \sigma^2_W + \sigma^2_L)^{0.5}$$

Where σ denotes standard deviation and σ^2 is the variance

The loss of load probability is the probability that X is less than zero or P(X<0). Define $X' = (X - \mu_x)/ \sigma_X$ as a standard normal variable. Then P(X<0) is the probability that X' is less than $-\mu_x / \sigma_X$ or $N(-\mu_x / \sigma_X)$ where N is the cumulative standard normal distribution function.

To calculate how much load LD can be taken on in NERC region r with the next increment $WD_{c,i}$ of class c wind supplied from wind region i without changing the loss of load probability, we now define the normal random variable $U = C + (W + WD_{c,i}) – (L + LD)$ with

$$\mu_U = \mu_C + \mu_W + \mu_{WDc,i} – \mu_L – \mu_{LD}$$

And $$\sigma^2_U = \sigma^2_C + \sigma^2_{W+WDc,i} + \sigma^2_{L+LD}$$

Where:

$WD_{c,i}$ is the generation from a small positive class c wind capacity addition in region i
LD is the increase in NERC region r load that maintains the loss of load probability.
Then the effective load carrying capacity of wind is $LD/WD_{c,i}$ when $P(U<0) = P(X<0)$
where $WD_{c,i} = \mu_{WDc,i} /CF$ with CF being the capacity factor of the class c wind capacity addition.

Finally, define the standard normal random variable $U' = (U – \mu_U)/ \sigma_u$. Then $P(U < 0) = P(U' < - \mu_U / \sigma_u = N(-\mu_U / \sigma_u)$. Then the effective load-carrying capacity of additional class c wind from region i supplied to NERC region r is $WCVmar_{c,I,r} = LD/ WD_{c,i}$ when

$$P(U<0) = P(X<0)$$

Or when

$$N(-\mu_U / \sigma_u) = N(-\mu_x / \sigma_X)$$

Or

$$- \mu_U / \sigma_u = - \mu_x / \sigma_X$$

Or

$$\mu_U / \sigma_u = \mu_x / \sigma_X$$

Or

$$[\mu_C + \mu_W + \mu_{WDc,i} – \mu_L – \mu_{LD}] / \sigma_u = \mu_x / \sigma_X$$

Or

$$\mu_{LD} = \mu_C + \mu_W + \mu_{WDc,i} – \mu_L – \mu_x * \sigma_u / \sigma_X$$

Or since the load added is not a random variable

$$LD = WD_{c,i} *CF + \mu_x * [1- \sigma_u / \sigma_X]$$

Thus, $WCVmar_{c,i,r} = LD / WD_{c,i} = CF – [\sigma_u / \sigma_X – 1] * \mu_x / WD_{c,i}$

Because the capacity value of wind is most important during the peak load periods, $WCVmar_{c,i,r}$ is calculated using the capacity value of wind during the peak load period of the NERC region. Similarly, the generation from conventional plants is assumed to be that of the peak load period, i.e. accounting for forced outages, but not planned outages, because they are generally planned for off-peak periods.

$$\mu_C = \sum_q CONVCAP_{q,n} * (1 - fo_q)$$

And $$\sigma^2_C = \sum_q numplants_{q,r} * plantsize_q^2 * fo_q * (1 - fo_q)$$

Where $numplants_{q,r} * plantsize_q = CONVCAP_{q,n}$

The expected load μ_L is assumed to be the input load for the NERC region.

The variance of the load σ^2_L is derived from the load-duration curve associated with a NERC region.

The variance of the wind generated by all the wind farms contributing to NERC region r is built up from the variance of the output of each individual wind farm and the covariance between those outputs. The standard deviation of the output of an individual wind farm is assumed to be the sum of the standard deviations of the outputs of the individual turbines in the wind farm, i.e. the outputs of the turbines within a wind farm are assumed to be perfectly correlated. The distribution of the wind itself is approximated with a Weibull distribution with shape parameter k = 2. The second parameter of the Weibull distribution of the wind speed is adjusted to ensure that the annual output of the wind turbine will produce the annual capacity factor of the wind turbine in the year 2000. The wind speed is translated to power output using the power curve of an individual wind turbine (Vestas 1650). Thus, the distribution on wind speed is translated to a distribution on wind power output. The variance in the wind power output is calculated from this wind power distribution.

WinDS assumes that the capacity factor associated with each class of wind power resource will improve with technological innovation in years after 2000. To translate the improved capacity factors into new estimates of the variance in the wind power distribution, a regression is used with the 2000 capacity factors as the independent variables that determine the variance, the dependent variables.

The variance of the wind output of individual wind farms is used to estimate the variance σ^2_{Wr} of the output from all wind farms contributing to the electric loads of a NERC region.

$$\sigma^2{}_{W_r} = \sum_{c,i} \sigma^2{}_{W_{c,i,r}} + 2 \sum_{\substack{c,i \\ cc,ii}} COVAR_{c,i,cc,ii.r}$$

Where $COVAR_{c,i,cc,ii,r}$ is the covariance between class c wind in region i and class cc wind in region ii.

$$COVAR_{c,i,cc,ii,r} = Corr_{c,i,cc,ii,r} * \sigma_{W_{c,i}} * \sigma_{W_{cc,ii}}$$

Where:

$CORR_{c,i,cc,ii,r}$ is the correlation between class c wind in region i and class cc wind in region ii. This correlation is assumed to be a linear function of the distance between the center of region i and that of region ii with full correlation (+1) of all wind of the same class in the same region and zero correlation at 500 miles separation. The correlation between two different wind classes in the same region is only 75%, under the assumption that two wind farms with different classes, although in the same region, are not collocated.

WCVold$_r$: The capacity value of wind built in previous periods, $WCVold_r$, is calculated each period. $WCVold_r$ is the amount of load that must be dropped per MW of wind to retain the same loss of load probability, if the wind is no longer available in NERC region r.

As with $WCVmar_{c,i,r}$, we define the random variable X as the sum of the conventional and wind generation minus the load.

$\mu_x = \mu_C + \mu_W - \mu_L$

Where:

μ denotes expected value
C is generation from all conventional power plants that deliver power to NERC region r
W is generation from all wind farms that deliver power to NERC region r
L is the load in NERC region r

If CF_r is defined as the average capacity factor of all the wind farms that deliver wind to NERC region r, then $\mu_W = WD_r{*}CF_r$

Since C, W, and L are statistically independent

$\sigma^2_X = \sigma^2_C + \sigma^2_W + \sigma^2_L$
$\sigma_X = (\sigma^2_C + \sigma^2_W + \sigma^2_L)^{0.5}$

Where σ denotes standard deviation and σ^2 is the variance

The loss of load probability is the probability that X is less than zero or P(X<0). Define $X' = (X - \mu_x)/\sigma_X$ as a standard normal variable. Then the probability that X is less than zero is the probability that X' is less than $-\mu_x / \sigma_X$ or $N(-\mu_x / \sigma_X)$ where N is the cumulative standard normal distribution function.

To calculate $WCVold_r$, we define the normal random variable U = C– (L - LD) similar to X in the calculation of $WCVmar_{c,i,r}$ except without the wind contribution. Then

$\mu_U = \mu_C - \mu_{L\text{-}LD}$

And $\sigma^2_U = \sigma^2_C + \sigma^2_{L\text{-}LD}$

Then the effective load-carrying capacity of all the wind supplied to NERC region r is $WCVold_r = LD/WDC_r$ when

$P(U<0) = P(X<0)$

Or when

$N(-\mu_U / \sigma_u) = N(-\mu_x / \sigma_X)$

Or

$- \mu_U / \sigma_u = - \mu_x / \sigma_X$

Or

$\mu_U / \sigma_u = \mu_x / \sigma_X$

Or

$[\mu_C - \mu_L + \mu_{LD}] / \sigma_u = \mu_x / \sigma_X$

Or

$\mu_{LD} = \mu_L - \mu_C + \mu_x * \sigma_u / \sigma_X$

Or since the load subtracted (LD) is not a random variable

$LD = \mu_L - \mu_C + \mu_x * \sigma_u / \sigma_X$

Thus

$WCVold_r = LD/WDC_r = (\mu_L - \mu_C + \mu_x * \sigma_u / \sigma_X) / WDC_r$

Or

$WCVold_r = (\mu_L - \mu_C - \mu_W + \mu_W + \mu_x * \sigma_u / \sigma_X) / WDC_r$

Or

$WCVold_r = (\mu_W - \mu_x *(1 - \sigma_u / \sigma_X)) / WDC_r$

Or

$WCVold_r = CF_r - \mu_x *(1 - \sigma_u / \sigma_X)) / WDC_r$

Or

$WCVold_r = CF - \mu_x *(1 - \sigma_u / \sigma_X)/WDC_r$

which looks very similar to the calculation of $WCVmar_{c,i,r}$

$WORmar_{c,i,r}$

$WORmar_{c,i,r}$ is the operating reserve requirement induced by the next MW of class c wind installed in region i that contributes generation to NERC region r. It is calculated as the difference in the operating reserve required with an increment $WD_{c,i,r}$ of additional wind capacity, minus that required with only the existing wind with the difference divided by the incremental wind capacity $WD_{c,i,r}$.

$$\mathrm{WORmar}_{c,i,r} = (\sqrt{NOR2 + wor2factor * \sigma^2_{W_r + WD_{c,i,r}}} - \sqrt{NOR2 + wor2factor * \sigma^2_{Wr}}) / WD_{c,i,r}$$

Where:

NOR2 is the variance of the usual operating reserve requirement

$$NOR2 = (Norfrac / resconf\,\mathrm{int} * (\sum_{n \in r} P_n - Norhydro * \sum_{n \in r} Conv_{n,hydro}))^2$$

Norfrac is the normal operating reserve fraction per MW of load.

resconfint is the multiplier on the variance of the load required to yield an adequate confidence interval

P_n is the peak load in PCA n in NERC region r

Norhydro is the amount by which the operating reserve can be reduced for each MW of hydroelectricity in the region

wor2factor is a multiplier on the wind variance to provide the appropriate impact on operating reserve requirements

$\sigma_{Wr+WDc,i,r}$ is the standard deviation of the output from all the wind generation consumed in NERC region r and that from the incremental capacity $WD_{c,i,r}$

σ_{Wr} is the standard deviation of the output from all the wind generation consumed in NERC region r

$WORold_{c,r}$

$WORold_{c,r}$ is the average operating reserve induced per MW of existing class c wind that is consumed in NERC region r. It is calculated as the difference in the operating reserve required with the existing wind capacity, minus that required were no wind used, divided by the total wind capacity contributing to NERC region r, W_r.

$\text{WORold}_{c,r} = (\sqrt{NOR2 + wor2factor * \sigma^2{}_{W_r}} - \sqrt{NOR2}) / W_r$

IWSurplusOld$_{in}$

IWsurplusold$_{in}$ is the expected fraction of generation from all the wind consumed in interconnect "in" that cannot be productively used, because the load is not large enough to absorb both it and the must-run generation from existing conventional sources. This situation occurs most frequently in the middle of the night when loads are small, base-load conventional plants are running at their minimum levels, and the wind is blowing.

To calculate IWsurplusold$_{in}$, we define a new random variable Y as the sum of the random variables for wind generation W and the must-run conventional base-load generation M minus the load L.

$Y = W + M – L$

Next, we define the surplus wind at any point in time, SU, as

If $Y < 0$, $SU = 0$

If $Y > 0$, $SU = Y$

Then, the expected total surplus μ_{SU} can be calculated from its density function f(s) and the density function of y, g(y) as follows:

$$\mu_{SU} = \int_{-\infty}^{\infty} sf(s)ds$$

$$\mu_{SU} = \int_{-\infty}^{0} sf(s)ds + \int_{0}^{\infty} sf(s)ds$$

$$\mu_{SU} = \int_{-\infty}^{0} yfy)dy + \int_{0}^{\infty} yg(y)dy$$

$$\mu_{SU} = 0 + \int_{0}^{\infty} yg(y)dy$$

Now if we assume, as we did in the WCVmar and WORmar calculations above, that by the central limit theorem, Y can be well approximated by a normal distribution, and we define the standard normal variable Y' as

$Y' = (Y – \mu_Y)/ \sigma_Y$

Then

$Y = Y' * \sigma_Y + \mu_Y$, and

$dy = \sigma_Y \, dY'$

Thus

$$\mu_{SU} = \int_{-\mu_Y/\sigma_Y}^{\infty} (y'\sigma_Y + \mu_Y) * g(y'\sigma_Y + \mu_Y) * \sigma_Y dy'$$

$$\mu_{SU} = \int_{-\mu_Y/\sigma_Y}^{\infty} ((\sigma_Y)^2 * y' * g(y'\sigma_Y + \mu_Y))dy' + \int_{-\mu_Y/\sigma_Y}^{\infty} \mu_Y * \sigma_Y * g(y'\sigma_Y + \mu_Y)dy'$$

Assuming Y is normally distributed as stated above:

$$\mu_{SU} = \int_{-\mu_Y/\sigma_Y}^{\infty} ((\sigma_Y)^2 * y' * (1/\sigma_Y\sqrt{2\Pi}) * \exp(-(y'\sigma_Y + \mu_Y)^2/(2\sigma_Y{}^2))dy'$$

$$+ \int_{-\mu_Y/\sigma_Y}^{\infty} \mu_Y * \sigma_Y (1/\sigma_Y\sqrt{2\Pi}) * \exp(-(y'\sigma_Y + \mu_Y)^2/(2\sigma_Y{}^2))dy'$$

$$\mu_{SU} = \int_{-\mu_Y/\sigma_Y}^{\infty} (\sigma_Y * y' / \sqrt{2\Pi} * \exp(-y'^2/2)dy' + \int_{-\mu_Y/\sigma_Y}^{\infty} \mu_Y / \sqrt{2\Pi} * \exp(-y'^2/2)dy'$$

$$\mu_{SU} = \sigma_Y / \sqrt{2\Pi} * \exp(-\mu_Y{}^2 / 2\sigma_Y{}^2) + \mu_Y (1 - N_{0,1}(-\mu_Y / \sigma_Y))$$

Where $N_{0,1}$ is the standard normal distribution with mean 0 and standard deviation 1.

Then $IWsurplusold_{in}$ is the difference between the expected surplus with wind, μ_{SU},, and the expected surplus were there no wind generation consumed in interconnect "in", μ_{SUN} , divided by the total wind capacity contributing to interconnect in, W_{in}. Or

$IWsurplusold_{in} = (\mu_{SU} - \mu_{SUN})/W_{in}$

Normally μ_{SUN} would be zero, as the conventional must run units would not be constructed in excess of the minimum load. However, with our assumption of a normal distribution for Y, we do introduce some non-zero probability that Y could be positive even if there were no wind, i.e. that the generation from must-run units could exceed load. Thus, it is important to calculate μ_{SUN} and to subtract it from μ_{SU} to remove the bulk of the error introduced by the normal distribution assumption. μ_{SUN} is calculated in exactly the same way as μ_{SU}, but with no wind included.

Must-run conventional capacity is defined as existing available (i.e., not in a forced outage state) coal and nuclear capacity times a minimum turn-down fraction, **MTDF**. The expected value of the must-run capacity of type q available at any given point in time, μ_{Mq} , is thus:

$\mu_{Mq} = CONVCAP_{q,in} * (1-FO_q) * MTDF_q$

Where:

$CONVCAP_{in,q}$ is the existing conventional capacity in interconnect in of type q
MTDF is
- 0.45 for old (built before the year 2000) coal plants
- 0.35 for new coal plants (built in 2000 or later, i.e. built within the model run time frame)
- 1.0 for nuclear plants

$IWSurplusMar_{c,i,in}$

$IWsurplusmar_{c,i,in}$ is the fraction of generation from the next MW of class c wind installed in wind supply region i destined for interconnect in that cannot be productively used because the load is not large enough to absorb both it and the must-run generation from existing conventional sources. It is calculated as:

$IWsurplusmar_{c,i,in} = (\mu_{SUi} - \mu_{SU})/100$

Where μ_{SUi} is calculated in exactly the same way as μ_{SU}, but with 100 MW of wind added in region i.

6. Retirement of capacity

All retiring wind turbines are assumed to be refurbished or replaced immediately, because the site is already developed with transmission access—and the cost of wind energy technology is only expected to get cheaper, while the cost of conventional generation is expected to get relatively more expensive due to fuel prices and emission controls. Wind capacity is replaced simply by assuming the wind capacity never decreases, i.e. the turbine capacity lasts indefinitely.[7] This does introduce a small error that is currently ignored. At the time that retiring wind turbines are replaced, they will most likely be replaced by state-of-the-art turbines, which can be expected to produce more energy and power per land area, and have higher capacity factors and lower costs than the machines they replace. This upgrading is not currently accounted for.

Similarly, storage (e.g., electrolyzers/hydrogen storage) at the wind site is assumed to be replaced immediately upon retirement. On the other hand, grid storage retires automatically when its assumed lifetime has elapsed.

Retirements of conventional generation can be modeled either as a fraction of remaining capacity each period (gas plants), through exogenous specification of planned retirements (currently used for nuclear, hydro, and oil/gas steam plants), or economic retirements (coal plants built before 2000).

Gas-fired capacity retirements: Because gas combustion turbines have been and continue to be used extensively as peaking plants, gas CT capacity retirement is assumed to have reached a steady state condition, best modeled by assuming a fixed fraction of existing capacity is retired each year. The fraction retired is set equal to 1/assumed plant operational lifetime.

$$CONVRET_{CT,n} = 2/ltime_{CT} * CONVOLD_{CT,n}$$

Where:

$\mathbf{CONVRET_{CT,n}}$ is the gas CT capacity in PCA n retiring in this period
$\mathbf{ltime_{CT}}$ is the assumed operational lifetime in years of gas CT capacity—it is assumed that the fraction retired in each year of the two year period is $1/ltime_{CT}$
$\mathbf{CONVOLD_{CT,n}}$ is the existing gas CT capacity in PCA n at the start of this period

After 2020, gas combined-cycle power plants are also retired at the fractional rate of 1/assumed plant operation lifetime. However, because such a high fraction of these plants were built in the four years between 2000 and 2004, the annual retirements between 2000 and 2020 are restricted to 1/20 of the capacity that existed before 2000.

Nuclear, hydroelectricity, and oil/gas steam turbines: In reality, the retirement of these plants is determined by a host of factors other than their operational viability and economics. Thus, in WinDS, where it is known that plants are scheduled to retire, that schedule is used. All capacity

[7] In deciding whether to invest in wind, the model uses a 20-year evaluation period, i.e. the turbines are not assumed to last indefinitely.

that does not have a scheduled retirement date is assumed to retire at a rate of 1/assumed plant operational lifetime.

$CONVRET_{n,q} = PRETIRE_{n,q} + 2/ltime_q * (CONVOLD_{n,q} – REMSCHED_{n,q})$

Where:

$CONVRET_{n,q}$ is the capacity in PCA n of type q retiring in this period
$PRETIRE_{n,q}$ is the planned retirement in this period in PCA n of capacity of type q
$ltime_q$ is the assumed operational lifetime in years of capacity of type q—it is assumed that the fraction retired in each year of the 2-year period is $1/ltime_{CT}$
$CONVOLD_{n,q}$ is the existing capacity in PCA n of type q at the start of this period
$REMSCHED_{n,q}$ is the remaining scheduled planned retirements in future periods in PCA n of capacity of type q

Coal-fired capacity retirements: Existing coal plants are retired based on both their assumed operational lifetimes and their variable operating costs relative to the costs of constructing and operating new gas combined-cycle plants.

$CONVRET_{n,q} = [2/ltime_q / (1+(CONVRETkn\_pgas_n / VCcoal_{n,q})^3))] * CONVOLD_{n,q}$

Where:

$CONVRETkn\_pgas_n$ is the levelized cost of power from a natural gas combined-cycle plant in PCA n
$VCcoal_{n,q}$ is the variable cost of operating a coal plant in PCA n of type q in this period

New coal plants are assumed to last beyond 2050, so there are no retirements of these plants.

7. Financial parameters

This section presents all the major financial parameters of WinDS. It begins with general economic parameters that are used in the WinDS economic calculations.

General Economic Parameters

d is a discount rate—as used in WinDS, it represents the annual investor return
d_r is a real discount rate, i.e. the rate of return above inflation
d_n is a nominal discount rate, i.e. the rate of return including inflation
E is the evaluation period or investment lifetime (years)
$PVA_{d,E}$ is the present value of annual \$1 payments for E years

$$PVA_{d,E} = \sum_{t=1}^{E} (1+d)^{-t} = (1 - 1/(1+d)^{L})/d$$

$PVA_{name,d,E,n}$ is the present value of annual fuel costs for technology q in PCA n escalating annually for E years.

$$PVA(q,n)_{d,E,e} = Fprice_{q,n} \sum_{t=1}^{E} (1+e)^{t} / (1+d)^{t}$$

$CRF_{d,E}$ is the capital recovery factor computed at discount rate d for E years, i.e. the fraction of the capital cost (CC) of an investment that must be returned each year to earn a rate of return equal to d if income taxes and financing are ignored.

$$CC = \sum_{t=1}^{E} CC * CRF_{d,E} / (1+d)^{t}$$

$$CRF_{d,E} = 1 / \sum_{t=1}^{E} (1+d)^{-t} = d / (1 - 1/(1+d)^{E})$$

Or

$$CRF_{d,E} = 1/PVA_{d,E}$$

Financial Parameters Specific to Wind

This subsection includes many of the cost parameters that are calculated for wind.

CW_c is the present value of the revenue required to pay for the capital cost of one MW of wind capacity (\$/MW) including interest during construction, finance, and taxes

$$CW_c = WCC_c * IDC / (1 - TR) * \begin{bmatrix} (1 - FF) + FF * PVDebt \\ - TR * (1 - ITCW/2) * PVDep - ITCW \end{bmatrix}$$

Where:

$\mathbf{WCC_c}$ is the overnight capital cost ($/MW) of the wind plant. WCC_c can be either a direct input (IWLC=0) or calculated based on a production learning curve. (IWLC = 1).

If learning-based improvements are allowed (ILC=1), then

$\mathbf{WCC_c}$ =WCC_o*[(1-costinstfrac)
*(1-$learnpar_{wind}$)^(log(WROW+$WindCap_{T\_delay}$/W_o)/log(2))
+ **constinstfrac*(1-**$learnpar_{wind}$**)^(log(**$WindCap_{T\_delay}$/W_UScapyr2000)/log(2))]

Where:

$\mathbf{WCC_o}$ is the overnight capital cost ($/MW) of wind without learning as input for the time period (i.e., includes any R&D driven changes over time, but not learning)
costinstfrac is the fraction of the capital cost associated with installation
$\mathbf{learnpar_{wind}}$ is the learning parameter for wind, or the % reduction in the capital cost of wind for each doubling of the installed capacity
WROW is the wind capacity installed in the rest of the world T_delay periods ago
T_delay is the time required for learning to impact the market, i.e. the learning delay in periods between installations and cost reductions
$\mathbf{WindCap_{T\_delay}}$ is the total national installed wind capacity T_delay periods ago
W_UScapyr2000 is the total national capacity in the year 2000
$\mathbf{W_o}$ is the total world wind capacity in the year 2000

IDC = multiplier to capture after-tax value of interest during construction

$$IDC = \sum_{t=1}^{CP} CONSF_t * [1 + (1 - TR) * \{(1 + i_c)^{CP-t} - 1\}]]$$

Where:

$\mathbf{CONSF_t}$ is the fraction of the capital cost incurred in year t of construction
$\mathbf{i_c}$ is the construction loan nominal interest rate
CP is the construction period

TR = combined federal and state marginal income tax rate
FF = fraction of the plant capital cost financed. It can be input or calculated as shown below (see DSCR discussion) to ensure that the required debt service coverage ratio (DSCR) is met.

PVDebt is the after-tax present value of debt payments.[8]

[8] Closed-form expression for the after-tax present value of the loan payments
Define Pt as the principal payment in year t, and i as the nominal interest rate, then the cost of the loan payments over the life L of the loan is:

$$PVDebt = \sum_{t=1}^{L} (P_t + (1-TR)I_t)/(1+d_n)^t$$
$$= CRF_{i,L} * (1-TR) * PVA_{d_n,L} + TR * (CRF_{i,L} - i)/(1+i) * PVA_{d_n^{'},L}$$

Where:

P_t is the principal portion of the finance payment made after the loan has been in place t years

I_t is the interest portion of the finance payment made after the loan has been in place t years

i = nominal interest rate for debt
L = financing period
d_n' = $(1+d_n)/(1+i) - 1$

ITCW = investment tax credit for wind
PVDep is the present value of depreciation

$$PVDep = \sum_{t=1}^{DP} Depf_t /(1+d_n)^t$$

Where:

$Depf_t$ = depreciation fraction in year t
DP = depreciation period

CWOMc is the present value of E years of operating costs including property taxes, insurance, and production tax credit ($/MW)

$$CWOM_c = WOMF_c * PVA_{d_r,E} + 8760 * CF_c * (WOMV_c * PVA_{d_r,E} - WPTC/(1-TR) * PVA_{d_r,PTCP})$$

$$\sum_{t=1}^{L} (P_t + (1-TR)I_t)/(1+d_n)^t = \sum_{t=1}^{L} (P_t + (1-TR) * (CRF_{i,L} - P_t))/(1+d_n)^t$$
$$= \sum_{t=1}^{L} CRF_{i,L} * (1-TR)/(1+d_n)^t + \sum_{t=1}^{L} P_t * TR/(1+d_n)^t$$
$$= \sum_{t=1}^{L} CRF_{i,L} * (1-TR)/(1+d_n)^t + TR\sum_{t=1}^{L} P_1 * (1+i)^{t-1}/(1+d_n)^t$$
$$= CRF_{i,L} * (1-TR) * \sum_{t=1}^{L} 1/(1+d_n)^t + TR * P_1/(1+i) * \sum_{t=1}^{L} (1+i)^t/(1+d_n)^t$$
$$= CRF_{i,L} * (1-TR) * PVA_{d_n,L} + TR * (CRF_{i,L} - i)/(1+i) * PVA_{d_n^{'},L}$$

where: d_n' = $(1+d_n)/(1+i) - 1$

Where:[9]

$WOMF_c$ is the fixed annual O&M cost of class c wind ($/MW-yr)
$WOMV_c$ is the variable O&M cost of class c wind ($/MWh)
WPTC is the production tax credit ($/MWh)
d_r is the real discount rate (assumes WOMF, WOMC, and WPTC do not change in real terms, i.e. they increase at the same rate as inflation)
PTCP is the period over which the production tax credit is received (years)
E is the evaluation period

CG_g is the increase in turbine price over cost due to rapid growth in wind deployment

$CG_1 = 0.01$
$CG_2 = (1\text{-Cost\_Inst\_Frac})*CW_6*GP*(BP_2-BP_1)/2$
$CG_3 = (1\text{-Cost\_Inst\_Frac})*CW_6*GP*(BP_2-BP_1+(BP_3-BP_2)/2)$
$CG_4 = (1\text{-Cost\_Inst\_Frac})*CW_6*GP*(BP_3-BP_1+(BP_4-BP_3)/2)$
$CG_5 = (1\text{-Cost\_Inst\_Frac})*CW_6*GP*(BP_4-BP_1+(BP_5-BP_4)/2)$
$CG_6 = (1\text{-Cost\_Inst\_Frac})*CW_6*GP*(BP_5-BP_1)$

Where:

CW_6 is the cost of a class 6 wind machine
GP is the growth penalty for each percent growth above the breakpoint
BP_k are breakpoints that discretize the growth price penalty
$(1<BP_1<BP_2<BP_3<BP_4<BP_5<BP_6)$

$CGinst_{ginst}$ is the increase in wind installation price over cost in growth bin ginst, due to rapid growth in wind deployment ($/MW)

$CGinst_1 = 0.01$
$CGinst_2 = \text{Cost\_Inst\_Frac}*CW_6*GPinst*(BP_2-BP_1)/2$
$CGinst_3 = \text{Cost\_Inst\_Frac}*CW_6*GPinst*(BP_2-BP_1+(BP_3-BP_2)/2)$
$CGinst_4 = \text{Cost\_Inst\_Frac}*CW_6*GPinst*(BP_3-BP_1+(BP_4-BP_3)/2)$
$CGinst_5 = \text{Cost\_Inst\_Frac}*CW_6*GPinst*(BP_4-BP_1+(BP_5-BP_4)/2)$
$CGinst_6 = \text{Cost\_Inst\_Frac}*CW_6*GPinst*(BP_5-BP_1)$

Where:

GPinst is the growth penalty for each percent growth above the breakpoint

[9] The use of a real discount rate in all the O&M calculations presumes that the O&M costs increase with inflation, i.e. that the real O&M cost is unchanging.

Setting the Finance Fraction in WinDS

The fraction of the capital cost of a wind farm that is financed can be input or endogenously estimated based on debt-service requirements. If calculated endogenously, the maximum fraction that can be financed is used. The fraction that can be financed is restricted by the Debt Service Coverage Ratio (DSCR). DSCR is the ratio of net pre-tax revenue to the debt payment (Debtpayment). WinDS assumes the net pre-tax revenue is equal to the revenue required to recover capital cost plus profit and tax benefits (e.g., production tax credit).

$$DSCR = \mathrm{CRF}_{\mathrm{d_n,E}} * (\mathrm{CW_c} + \mathrm{WPTC} * 8760 * \mathrm{CF_c} / (1 - \mathrm{TR}) * \mathrm{PVA}_{\mathrm{d_r,PTCP}}) / \mathrm{Debtpayment}$$

Where:

$$Debtpayment = FF * WCC * IDC * CRF_{i,L}$$

Solving the DSCR equation for the finance fraction (which is embedded in $\mathrm{CW_c}$ as well) yields

$$\begin{aligned} FF = {} & CRF_{d,E} * (\mathrm{WPTC} * 8760 * \mathrm{CF_c} / (1 - \mathrm{TR}) * \mathrm{PVA}_{\mathrm{d_r,PTCP}} \\ & + WCC * IDC / (1 - TR) * (1 - TR * (1 - ITCW/2) * PVDep - ITCW)) / \\ & (WCC * IDC * [DSCR * CRF_{i,L} + (1 - PVDebt) * CRF_{d,E} / (1 - TR)]) \end{aligned}$$

Financial Parameters Specific to Conventional Technologies

This section includes many of the cost parameters that are calculated in WinDS for conventional technologies. Inasmuch as some of these are substantively the same as those calculated for wind, the reader will be referred to the above wind parameter subsection.

CCONVq is the present value of the revenue required to pay for the capital cost of one MW of capacity of generating technology q ($/MW) including interest during construction, finance, and taxes. It is calculated in a manner analogous to that for wind.

$$CCONV_q = CCC_q * \left(CRF_{d_r,E} / CRF_{d_r,L_q} \right) * IDC / (1 - TR) * \begin{bmatrix} (1 - FF) + FF * PVDebt \\ - TR * (1 - ITC_q / 2) * PVDep - ITC_q \end{bmatrix}$$

Where:

$\mathbf{CCC_q}$ is the overnight capital cost ($/MW) of the generation plant. $\mathbf{CCC_q}$ can be either a direct input (ILC=0) or calculated based on a production learning curve. (ILC = 1).

If learning-based improvements are allowed (ILC=1), then

$\mathbf{CCC_q}$ $=\mathrm{CCC_o}*(1\text{-learnpar}_q)$^$(\log(\mathrm{CONVOLDdelay}_q/\mathrm{USCapyr2000}_q)/\log(2))$

Where:

> **CCC_o** is the overnight capital cost of generating technology q without learning as input for the time period (i.e., includes any R&D driven changes over time, but not learning)
> **$CONVOLDdelay_q$** is the total national installed wind capacity learndelay periods ago
> **learndelay** is the learning delay between installations and cost reductions
> **$USCapyr2000_q$** is the total national capacity of generation technology q in the year 2000
> **$learnpar_q$** is the learning parameter for generation technology q or the % reduction in the capital cost for each doubling of the installed capacity
> **L_q** is the economic lifetime of technology q (years)
> **FF** is the finance fraction which must be input for conventional technologies (unlike the endogenous calculation option for wind described above)
> See the calculation of CW_c for the definition of the other inputs for CCC_q

$CCONVV_{n,q}$ is the present value of the variable cost of operating technology q in PCA n for E years

$$CCONVV_{n,q} = CVarOM_q * PVA_{d_r,E} + Fprice_{q,n} * cheatrate_q * PVA(n,q)_{d_r,E,e}$$

Where:

> **$CvarOM_q$** is the variable O&M cost for technology q ($/MWh)
> **$Fprice_{q,n}$** is the cost of the input fuel ($/MMBtu)
> **$cheatrate_q$** is the heat rate for technology q

$CCONVF_q$ is the present value of the fixed costs of operating technology q for E years ($/MW)

$$CCONVF_q = COMF_q * PVA_{dr,E}$$

Where:

> **$COMF_q$** is the annual fixed O&M cost for plant type q ($/MW-yr)

$CSRV_{n,q}$ is the present value of the variable cost of spinning reserve provided for E years in PCA n ($/MWh). The cost represents the cost of operating the plant at part-load. A linear program cannot ordinarily capture part-load efficiency, because it is highly nonlinear with the level of operation. WinDS assumes that if spinning reserve is provided, the maximum amount is provided in the time slice, the plant is operating at MinSRq*CONVCAPq,n. Thus, the cost of spinning reserve can be estimated by solving the following for CSRVn,q:

$$CCONVV_{q,n} * (MinSR_q * CONV_{q,n}) / PLEffFactor_q$$
$$= CCONVV_{q,n} * (MinSR_q * CONV_{q,n}) + (1 - MinSR_q) * CONV_{q,n} * CSRV_{n,q}$$

or

$$CSRV_{n,q} = MinSR_q / (1 - MinSR_q) * CCONVV_{q,n} * (1 / PLEffFactor_q - 1)$$

<u>Transmission Cost Parameters</u>

$CCT_{n,p}$ is the present value of transmitting 1 MWh of power for each of E years between PCAs n and p ($/MWh)

$$CCT_{n,p} = (Dis_{n,p}*TOCOST + POSTSTWCOST*PostStamp_{n,p}))*PVA_{dn,E}$$

Where:

$Dis_{n,p}$ is the distance in miles between the center of PCAs n and p
TOCost is the cost per mile for using existing transmission lines ($/MWh-mile).
POSTSTWCOST is the cost of using transmission that crosses a PCA ($/MWh)
$PostStamp_{n,p}$ is the number of PCAs that must be crossed to move from PCA n to PCA p. If p is not the same as n, PCA p is counted as one PCA to be crossed.

$TPCA\_CG_{tpca\_g}$ is the difference between the price and cost of transmission in transmission growth bin tpca_g ($/MW-mile).

$TPCA\_CG_1 = 0.01$

$TPCA\_CG_2 = TNCost * TPCAGP * (TPCACC(TPCABP_2) – TPCACC(TPCABP_1))/2$

$TPCA\_CG_3 = TNCost * TPCAGP * [(TPCACC(TPCABP_2) – TPCACC(TPCABP_1))+(TPCACC(TPCABP_3) – TPCACC(TPCABP_2))/2]$

$TPCA\_CG_4 = TNCost * TPCAGP * [(TPCACC(TPCABP_3) – TPCACC(TPCABP_1))+(TPCACC(\_TPCABP_4) – TPCACC(TPCABP_3))/2]$

$TPCA\_CG_5 = TNCost * TPCAGP * [(TPCACC(TPCABP_4) – TPCACC(TPCABP_1))+(TPCACC(TPCABP_5) – TPCACC(TPCABP_4))/2]$

$TPCA\_CG_6 = TNCost * TPCAGP * [TPCACC(TPCABP_5) – TPCACC(TPCABP_1)]$

Where:

TPCA_GP is the percent increase in the cost of transmission for each percent growth over the base amount

$TPCACC(TPCABP_k)$ is the fractional breakpoint associated with step k of the growth curve

$TPCACC(TPCABP_5) > TPCACC(TPCABP_4) > TPCACC(TPCABP_3) > TPCACC(TPCABP_2) > TPCACC(TPCABP_1 > 1)$

CILA is the present value of the cost to a utility for 1 MW of interruptible load over the evaluation period of E years ($/MW)

$$CILA = CIL * PVA_{dr,E}$$

Where CIL is the annual cost of one MW of interruptible service

$\mathbf{CIL_{ilg}}$ is the present value over the evaluation period of the cost of higher levels of interruptible load than the base level ($/MWh). A supply curve is used for each PCA to capture the cost of larger amounts of interruptible load supply. The subscript ilg denotes the discrete step of the supply curve. For the ilg step of the supply curve, CIL_{ilg} provides the additional cost of interruptible load over the base amount.

$CIL_1 = 0.01$

$CIL_2 = CILA * ILGP * (CIL\_SC(ILBP_2) – CIL\_SC(ILBP_1))/2$

$CIL_3 = CILA * ILGP * [(CIL\_SC(ILBP_2) – CIL\_SC(ILBP_1))+(CIL\_SC(ILBP_3) – CIL\_SC(ILBP_2))/2]$

$CIL_4 = CILA * ILGP * [(CIL\_SC(ILBP_3) – CIL\_SC(ILBP_1))+(CIL\_SC(ILBP_4) – CIL\_SC(ILBP_3))/2]$

$CIL_5 = CILA * ILGP * [(CIL\_SC(ILBP_4) – CIL\_SC(ILBP_1))+(CIL\_SC(ILBP_5) – CIL\_SC(ILBP_4))/2]$

$CIL_6 = CILA * ILGP * [CIL\_SC(ILBP_5) – CIL\_SC(ILBP_1)]$

Where:

ILGP is the fractional increase in the cost of interruptible load for each percent increase over the base amount

$\mathbf{CIL\_SC(ILBP_k)}$ is the fractional breakpoint associated with step k of the supply curve ($CIL\_SC(ILBP_5 > CIL\_SC(ILBP_4 > CIL\_SC(ILBP_3 > CIL\_SC(ILBP_2 > CIL\_SC(ILBP_1 > 1$)

Hydrogen Cost Parameters

$\mathbf{CGelectrolyzer_{hebp}}$ is the increase in growth step hebp in electrolyzer price over cost due to rapid growth in electrolyzer deployment ($/kg-year)

$\mathbf{CGelectrolyzer_1} = 0.01$

$\mathbf{CGelectrolyzer_2} = CCH2electrolyzer * GPElec*(EGR(HEBP_2)-EGR(HEBP_1))/2$

$\mathbf{CGelectrolyzer_3} = CCH2electrolyzer * GPElec*(EGR(HEBP_2)-EGR(HEBP_1)+(EGR(HEBP_3)-EGR(HEBP_2))/2)$

$\mathbf{CGelectrolyzer_4} = CCH2electrolyzer * GPElec*(EGR(HEBP_3)-EGR(HEBP_1)+(EGR(HEBP_4)-EGR(HEBP_3))/2)$

$\mathbf{CGelectrolyzer_5} = CCH2electrolyzer * GPElec*(EGR(HEBP_4)-EGR(HEBP_1)+(EGR(HEBP_5)-EGR(HEBP_4))/2)$

$\mathbf{CGelectrolyzer_6} = CCH2electrolyzer * GPElec*(EGR(HEBP_5)-EGR(HEBP_1))$

Where:

CCH2electrolyzer is the cost of an electrolyzer ($/kg-yr)

GPElec is the growth penalty for each percent growth above the breakpoint

$\mathbf{EGR(HEBP_k)}$ are breakpoints that discretize the growth price penalty

$1<EGR(HEBP_1)<EGR(HEBP_2)<EGR(HEBP_3)<EGR(HEBP_4)<EGR(HEBP_5))$

$\mathbf{CGSMR_{hsmrbp}}$ is the increase in growth step hsmrbp in the price of a steam methane reformer over cost due to rapid growth in steam methane reformer deployment ($/kg-year)

CGSMR$_1$ = 0.01
CGSMR$_2$ = CCH2ng_reformer * GPSMR*(SMRGR(HSMRBP$_2$)-SMRGR(HSMRBP$_1$))/2
CGSMR$_3$ = CCH2 ng_reformer * GPSMR*(SMRGR(HSMRBP$_2$)-SMRGR(HSMRBP$_1$)+(SMRGR(HSMRBP$_3$)-SMRGR(HSMRBP$_2$))/2)
CGSMR$_4$ = CCH2 ng_reformer * GPSMR*(SMRGR(HSMRBP$_3$)-SMRGR(HSMRBP$_1$)+(SMRGR(HSMRBP$_4$)-SMRGR(HSMRBP$_3$))/2)
CGSMR$_5$ = CCH2 ng_reformer * GPSMR*(SMRGR(HSMRBP$_4$)-SMRGR(HSMRBP$_1$)+(SMRGR(HSMRBP$_5$)-SMRGR(HSMRBP$_4$))/2)
CGSMR$_6$ = CCH2 ng_reformer * GPSMR*(SMRGR(HSMRBP$_5$)-SMRGR(HSMRBP$_1$))

Where:

CCH2$_{\mathbf{ng\_reformer}}$ is the cost of a steam methane reformer ($/kg-yr)
GPSMR is the growth penalty for each percent growth above the breakpoint
SMRGR(HSMRBP$_{\mathbf{k}}$**)** are breakpoints that discretize the SMR growth price penalty
1<SMRGR(HSMRBP$_1$)<SMRGR(HSMRBP$_2$)<SMRGR(HSMRBP$_3$)<SMRGR(HSMRBP$_4$)<SMRGR(HSMRBP$_5$))

CGFC$_{\mathbf{hfcbp}}$ is the increase in growth step hfcbp in the price of a steam methane reformer over cost due to rapid growth in steam methane reformer deployment ($/kg-year)
CGFC$_1$ = 0.01
CGFC$_2$ = CCH2fuelcell * GPFC*(FCGR(HFCBP$_2$)-FCGR(HFCBP$_1$))/2
CGFC$_3$ = CCH2 fuelcell * GPFC*(FCGR(HFCBP$_2$)-FCGR(HFCBP$_1$)+(FCGR(HFCBP$_3$)-FCGR(HFCBP$_2$))/2)
CGFC$_4$ = CCH2 fuelcell * GPFC*(FCGR(HFCBP$_3$)-FCGR(HFCBP$_1$)+(FCGR(HFCBP$_4$)-FCGR(HFCBP$_3$))/2)
CGFC$_5$ = CCH2 fuelcell * GPFC*(FCGR(HFCBP$_4$)-FCGR(HFCBP$_1$)+(FCGR(HFCBP$_5$)-FCGR(HFCBP$_4$))/2)
CGFC$_6$ = CCH2 fuelcell * GPFC*(FCGR(HFCBP$_5$)-FCGR(HFCBP$_1$))

Where:

CCH2$_{\mathbf{fuelcell}}$ is the cost of a steam methane reformer ($/kg-yr)
GPFC is the growth penalty for each percent growth above the breakpoint
FCGR(HFCBP$_{\mathbf{k}}$**)** are breakpoints that discretize the FC growth price penalty
1<FCGR(HFCBP$_1$)<FCGR(HFCBP$_2$)<FCGR(HFCBP$_3$)<FCGR(HFCBP$_4$)<FCGR(HFCBP$_5$))

Appendix A

Variables and Parameters Used in WinDS

Variable	Units	Description
a_j	fraction	The fraction of existing transmission line j capacity available to wind
BASE_ELEC	MW	The national electrolyzer capacity at the start of the period
BASE_FCELL	MW	The national fuel cell capacity at the start of the period
BASE_SMR	Kg/year	The national SMR capacity at the start of the period
BASETPCA	MW	The national transmission capacity at the start of the period
BASE_WIND	MW	The national wind capacity at the start of the period
$BASE\_WINDinst_i$	MW	The region i wind capacity at the start of the period
$btech_q$		A binary parameter that is 1 if q is a base-load technology and 0 otherwise
c	integer	Subscript indicating the wind class
C		Generation from all conventional power plants that deliver power to NERC region r
$CAOMH_{technology\ name}$	\$/kWh or \$/kg	Present value of the variable O&M cost (including any production tax credit) for a unit of production (for hydrogen or storage technologies) in each year of the evaluation period
Carboncost	(\$/pound carbon)	**C**ost of carbon emissions
carbtaxmax	\$/ton carbon	Ultimate carbon tax level
ctaxdiscsum		Multiplier to convert annual cost of carbon to present value cost over the evaluation period
CCC_q	\$/MW	The turnkey capital cost per MW of plant type q
$CCH2_{technology\ name}$	\$/MW or \$/(kg/year)	Capital cost of a hydrogen or storage technology
$CCONVF_q$	\$/MW	The present value over the evaluation period of the fixed O&M costs of plant type q
$CCONV_q$	\$/MW	The capital cost of plant type q after accounting for taxes and finance
$CCONVV_{n,q}$	\$/MWh	The present value of the variable operating and fuel costs for one MWh in each of E years in PCA n for technology q

$CCT_{n,p}$	\$/MWh	The present value of transmitting 1 MWh of power for each of E years between PCA's n and p
CF_c	fraction	Annual capacity factor of new onshore wind systems of class c in the time period being run
$CFcofd_c$	fraction	Annual capacity factor of new deep offshore wind systems of class c in the time period being run
$CFcofs_c$	fraction	Annual capacity factor of new shallow offshore wind systems of class c in the time period being run
$CF\_corr_{c,i,m}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for each time slice m
$CF\_corrofd_{c,i,m}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for each time slice m
$CF\_corrofs_{c,i,m}$	fraction	Correction to the annual capacity factor for shallow offshore wind for class c in region i for each time slice m
$CF\_corrps_{c,i,s}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for the peak time slice in season s
$CF\_corrpsofd_{c,i,s}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for the peak time slice in season s
$CF\_corrpsofs_{c,i,s}$	fraction	Correction to the annual capacity factor for shallow offshore wind in region i for class c for the peak time slice in season s
$CF\_corrs_{c,i,s}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for season s
$CF\_corrsofd_{c,i,s}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for season s
$CF\_corrsofs_{c,i,s}$	fraction	Correction to the annual capacity factor for shallow offshore wind for class c in region i for season s
$CfixOMH_{\text{technology name}}$	\$/MWh or \$/kg H_2	Fixed O&M cost for a unit of production capacity (for hydrogen or storage technologies)
$CFO_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c onshore wind on existing (at the start of the analysis time frame) lines in region i

$CFofs_c$		Capacity factor for new shallow offshore wind at a class c site
$CFofd_c$		Capacity factor for new deep offshore wind at a class c site
$CFOofd_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c deep offshore wind on existing (at the start of the analysis time frame) lines in region i
$CFOofs_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on existing (at the start of the analysis time frame) lines in region i
$CFTO_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c onshore wind on new (built in this period) lines in region i
$CFTOofd_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c deep offshore wind on new (built in this period) lines in region i
$CFTOofs_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on new (built in this period) lines in region i
$CGelectroyzer_{hebp}$	$/MW	Increase in electrolyzer price over cost in growth bin hebp, due to rapid growth in electrolyzer deployment
$CGFC_{hfcbp}$	$/MW	Increase in fuel cell price over cost in growth bin hfcbp, due to rapid growth in fuel cell deployment
CG_g	$/MW	Increase in turbine price over cost in growth bin g, due to rapid growth in wind deployment
$CGinst_{ginst}$		Increase in wind installation price over cost in growth bin ginst, due to rapid growth in wind deployment
Cgridconnect	$/MW	The cost of connecting a generator to the grid – excludes transmission spur cost
$CGSMR_{hsmrbp}$	$/MW	Increase in steam methane reformer price over cost in growth bin hsmrbp due to rapid growth in steam methane reformer deployment
$cheatrate_q$	MBtu/MWh	Heat rate for generator type q
$CHEFF_{technology\ name}$	MWh/kg or kg/MWh or kg/MBtu	Efficiency of hydrogen/storage

CIL_{ilg}	$/MW	Present value of the additional cost of interruptible load beyond the base cost (see CILA) in step ilg of the interruptible load supply curve
CIL_n	$/MWh	Present value over the evaluation period of the base cost of interruptible load in PCA n
CILA	$/MW	CILA is read in as the annual base cost of one MW of interruptible service and is converted to the present value of the base cost of one MW of interruptible service purchased in each year of the evaluation period
$CIL\_SC(ILBP_k)$	fraction	The fractional breakpoint associated with step k of the supply curve
$class_{c,i}$		Binary parameter that indicates whether class c onshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best onshore wind to consider in this time period
$classofd_{c,i}$		Binary parameter that indicates whether class c deep offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best deep offshore wind to consider in this time period
$classofs_{c,i}$		Binary parameter that indicates whether class c shallow offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best shallow offshore wind to consider in this time period
$classT_{c,i}$		Binary parameter that indicates whether class c onshore wind in region i that uses new (installed in this time period) transmission is the best onshore wind to consider in this time period
$classTofd_{c,i}$		Binary parameter that indicates whether class c deep offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period
$classTofs_{c,i}$		Binary parameter that indicates whether class c shallow offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period
$Coal\_old\_prev_{n,q}$	MW	The capacity of coal-fired generation in PCA n of type q at the end of the previous two-year period

$Coal\_old\_prev_{coal\text{-}old\text{-}1,n}$	MW	The capacity of coal-fired generation with scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous two-year period
$Coal\_old\_prev_{coal\text{-}old\text{-}2,n}$	MW	The capacity of coal-fired generation without scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous two-year period
$coalowsul_{n,coal\text{-}old\text{-}1}$	MWh	Total conventional generation from coal-fired generation with scrubbers that existed before the analysis time frame in PCA n using low-sulfur coal
$coalowsul_{n,coal\text{-}old\text{-}2}$	MWh	Total conventional generation from coal-fired generation without scrubbers that existed before the analysis time frame in PCA n using low sulfur coal
$coalowsul_{n,q}$	MWh	Total conventional generation from coal plants of type q in PCA n using low-sulfur coal
$coallowsulinccost_n$	$/MMBtu	The additional cost of low sulfur coal relative to high-sulfur coal in PCA n
coallowsulpolred	tons/MWh	The delta (tons) in SO_2 emissions per MWh between high sulfur and low sulfur coal
$COMF_q$	$/MW-yr	The annual fixed O&M cost for plant type q
$CONSF_t$	fraction	The fraction of the capital cost in year t of construction
$CONTRACTCAP_{n,p}$	MW	The electric capacity contracted by PCA p to be received from PCA n
$CONVCAP_{n,q}$	MW	A variable for the capacity of generator type q installed in PCA n
$CONVCAPC_q$	MW	The effective load-carrying capability of conventional capacity type q
$CONVCAP_{in,q}$		The existing conventional capacity in interconnect in of type q
$CONVGEN_{m,n,q}$	MW	A variable for the capacity of generator type q operating during time slice m in PCA n
$CONVPGEN_{m,n,q}$	MW	A variable for the capacity of generator type q operating in peak time slice m in excess of the generation by type q in non-peak time slices ($CONVPGEN_{m,n,q}$ will be zero for off-peak time slices).
$CONVOLD_{n,q}$	MW	Capacity in PCA n of generator type q at the end of the previous time period
$CONVpol_{pol,q}$	Lb/MWh or ton/MWh	Emission of pollutant pol with each MWh of generation by technology q
$CONVRET_{n,q}$	MW	The capacity in PCA n of generator type q

		retired in this period.
$CONVRETkn\_pgas_n$		The levelized cost of power from a natural gas combined-cycle plant in PCA n
$CONVT_{m,n,p}$	MW	Variable for the conventional capacity in time slice m transmitted from PCA n to PCA p
$CORR_{c,i,cc,ii,r}$		The correlation between class c wind in region i and class cc wind in region ii.
$COVAR_{c,i,cc,ii,r}$		The covariance between class c wind in region i and class cc wind in region ii
costinstfrac	fraction	The fraction of the capital cost of wind associated with installation
CP		The construction period
$cpop_{c,i}$		A multiplier on the capital cost of transmission lines for wind to account for increased siting/land costs in highly populated areas. The value varies between 1 and 2 as a linear function of population density in the vicinity of class c wind sites in region i
CQS	\$/MW	The cost to modify a combustion turbine to provide a quick-start capability
$CRF_{d,E}$		The capital recovery factor computed at discount rate d for E years, i.e. the fraction of the capital cost of an investment that must be returned each year to earn a rate of return equal to d if income taxes and financing are ignored
$cslope_{c,i}$	degree	Terrain slope for class c wind sites in region i
cslopeTcostfactor		Fractional increase in transmission capital cost for each degree of terrain slope
cslopeWcostfactor		Fractional increase in wind capital cost for each degree of terrain slope
$CSRV_{n,q}$	\$/MWh	The present value over E years of the operating and fuel cost of spinning reserve in PCA n of type q
cur_year		The first year of the two-year period for which the optimization is being performed. Cur_year is always the even-numbered year
$CvarOM_q$	\$/MWh	The variable O&M cost for technology q
CW_c	\$/MW	Capital cost of class c onshore wind including cost reductions through learning-by-doing, and the present value of taxes and financing
$CWcofs_c$	\$/MW	Capital cost of class c shallow offshore wind including cost reductions through learning-by-doing, and the present value of taxes and

		financing.
$CWcofd_c$	$/MW	Capital cost of class c deep offshore wind including cost reductions through learning-by-doing, and the present value of taxes and financing.
CWOMc	$ / MW	The present value of E years of fixed and variable operating costs for class c onshore wind including production tax credits
$CWOMcofs_c$	$ / MW	The present value of E years of fixed and variable operating costs for class c shallow offshore wind including production tax credits
$CWOMcofd_c$	$ / MW	The present value of E years of fixed and variable operating costs for class c deep offshore wind including production tax credits
d	fraction	Discount rate
$Depf_t$	fraction	Depreciation fraction in year t
DEretper		The period during which the older remaining (i.e, not yet retired) distributed electrolyzers were constructed
$DISFCELL\_CAP_n$	MW	Variable for new distributed fuel cell capacity within PCA n using hydrogen from distributed electrolyzers
$DISFCELL\_CAP\_OLD_{n,t}$		Distributed fuel cell capacity built in PCA n in period t using hydrogen from distributed electrolyzers
$dis_{i,j}$	miles	Distance between the center of regions i and j
$dis_{p,n}$	miles	Distance between the center of PCAs p and n
d_n	fraction	Nominal discount rate
DP	years	Depreciation period for income tax purposes
d_r	fraction	Real discount rate
E	years	The evaluation period or investment lifetime
$Ecostescal_{n,q}$		Annual real price escalation of fuel used by technology q in PCA n
$EGR(HEBP_{k)}$		Breakpoints that discretize the growth price penalty
ELE_i	MW	Variable for the new storage conversion (e.g., electrolyzers/hydrogen storage) capacity at the onshore wind site in region i
$fcellcapacity_i$	MW	Variable for new generator (e.g., fuel cell) capacity fueled by the storage medium (e.g., hydrogen) produced from onshore wind in region i

$fcelldest_{n,s}$	MWh	Variable for electricity consumed in PCA n in season s generated from generators (e.g., fuel cells) fueled by stored energy (e.g., hydrogen) from new wind
$fcelldestold_{n,s}$	MWh	The generator (e.g., fuel cell) output in season s from wind-sited generators fueled by stored energy (e.g., fuel cells) built in previous periods that ship power to PCA n
$fcell\_inregion_{c,j,s}$	MWh	Variable for electricity generated from new generators fueled by stored energy (e.g., fuel cells fueled by hydrogen) from new class c wind resources in wind supply region j for use in the same wind demand region j during season s
$fcell_{i,r,s}$	MWh	Variable for electricity generated from new generators fueled by stored energy (e.g., fuel cells using hydrogen) from wind in wind supply region i for use in NERC region r during season s
FCretper		Period during which the older remaining (i.e. not yet retired) fuel cells were constructed
$FCGR(HFCBP_k)$		Breakpoints that discretize the fuel cell growth price penalty
FF	fraction	Fraction of the capital cost of a plant that is financed
Fo_q	fraction	Forced outage rate for generator type q
$Fprice_{q,n}$	\$/MMBtu	The cost of the input fuel
GPElec		The growth penalty for electrolyzers for each percent growth above the breakpoint
GPFC		The growth penalty for fuel cells for each percent growth above the breakpoint
GPSMR		The growth penalty for steam methane reformers for each percent growth above the breakpoint
Gt_g	fraction	A fractional multiplier on the national wind capacity that defines the national wind capacity in step g of the wind turbine price multiplier for rapid growth
$Gtinst_{ginst}$	fraction	A fractional multiplier on the wind capacity in a region that defines the region's wind capacity in step ginst of the wind installation price multiplier for rapid growth
$grid\_2\_welectrolysis_{i,m}$	MWh	Grid-supplied electricity to new storage (e.g., electrolyzers/hydrogen storage) at grid-connected wind farms in region i in time slice m

$grid\_2\_welectrolysis\_inregion_{i,m}$	MWh	Grid-supplied electricity to new storage (e.g., electrolyzers/hydrogen storage) at wind farms in region i in time slice m whose electric generation is used within the region
H2energy		Annual production of energy for storage (e.g., hydrogen)
H2energy_summerday		Energy produced for storage during a summer day (e.g., hydrogen)
$H2\_loadprofile_m$	fraction	Fraction of annual hydrogen production from nonwind production technologies that occurs in time slice m
$h2stored\_summerday_i$		Energy storage capacity (e.g., electrolyzers/hydrogen storage) required to meet the on-peak operation of the generators operated from storage (e.g., fuel cells) at wind sites in region i
H2PRICE	$/kg	Price that hydrogen will receive in the marketplace in this time period
H2_prodnhours		The number of hours that nonwind hydrogen production facilities are operated each year
$H2storagecapacity_i$		Variable for new hydrogen storage capacity in region i
H3		The peak time slice in the summer season
$HEGBIN_{hebp}$	MW	Variable for new national storage-conversion process (e.g., electrolyzer) capacity in growth bin hebp
$HEGBINCAP_{hebp}$	fraction	Fractional growth in national storage-conversion process (e.g., electrolyzer) capacity in growth step hebp
He_n	MWHr	Annual hydro energy available in PCA n
$HFCGBIN_{hfcbp}$	MW	Variable for new national generator capacity fueled from storage (e.g., fuel cell) in growth bin hfcbp
$HFCGBINCAP_{hfcbp}$	fraction	Fractional growth in national conversion-storage capacity (e.g., electrolyzer/hydrogen storage) in growth step hfcbp
$hfdemand_j$	Kg/year	Maximum annual demand for hydrogen as a transportation fuel for light-duty vehicles in region j in the base year
hfdemand_escal	fraction	Annual escalation in the demand for light-duty vehicle fuels
hfd_j	kg	Variable for hydrogen fuel produced by new wind installations connected to the grid for consumption in region j
$hfdiselec\_2\_fcell_{j,m}$	kg	Variable for hydrogen fuel produced by both new and old distributed electrolyzers in

		region j in time slice m for storage for later use in a fuel cell
$hfdiselec_j$	kg	Variable for hydrogen fuel produced by both new and old distributed electrolyzers in region j for use as a transportation fuel
$HF\_DISELEC\_CAP_j$	MW	Variable for new distributed conversion to storage capacity (e.g., electrolyzer/hydrogen storage) powered by the grid and located in region j
$HF\_DISELEC\_CAPOLD_{j,t}$	MW	The distributed conversion (e.g., electrolyzer) capacity built in period t in region j
$hfdold_j$	Kg	Hydrogen transportation fuel supplied by all remaining hydrogen production facilities built in prior periods
$hf\_inregion_{c,hscp,i}$	Kg	Variable for hydrogen fuel produced from class c wind from step hscp in region i for the supply curve that provides the cost of hydrogen fuel shipment from wind in the region to city load centers within the same region i
$hf\_inregion\_cost_{c,hscp,j}$	$/kg	Cost associated with step hscp for the shipment of hydrogen fuel from a class c wind site within region i to a city within the region
hfs_i	kg	A variable for the hydrogen fuel produced in region i from new onshore wind installations that are connected to the grid
$hf_{i,j}$	kg	A variable for hydrogen fuel shipped to region j from new onshore wind installations in region i that are connected to the grid
$HF\_STEAMREF\_CAP_j$	Kg/year	A variable for new steam methane reformer capacity in region j
$HF\_STEAMREF\_CAPOLD_{j,t}$	Kg/year	The SMR capacity built in period t in region j
$hfsteamref_j$	kg	A variable for hydrogen fuel produced by both new and old steam methane reformers in region j
H_m	Hr	The number of hours in a year in time slice m
$HSMRGBIN_{hsmrbp}$	Kg/year	Variable for new national steam methane reformer capacity in growth bin hsmrbp
$HSMRGBINCAP_{hsmrbp}$	fraction	Fractional growth in national steam methane reformer capacity in growth step hsmrbp
i	integer	Subscript indicating a wind supply region.
i_c	fraction	The construction loan interest rate
IDC		Multiplier to capture after-tax value of interest during construction
IL_n	MW	Interruptible load in PCA n

$ILGt_{ILG}$		The fraction of peak demand in step ILG of the supply curve
ILGP	fraction	The fractional increase in the cost of interruptible load for each percent increase over the base amount
$ILt_{ilg,n}$	MW	Interruptible load used in PCA n from supply curve step ilg
In	fraction	Nominal interest rate for debt
ind_elec_adder	$/MWh	Additional cost beyond the wholesale cost for delivering grid electricity to distributed electrolyzers and electrolyzers at the wind site
inf	fraction	Inflation rate
I_t		The interest portion of the finance payment made after the loan has been in place t years
ITCW	$	Investment tax credit for wind
$IWSurplus_{c,i,in}$	fraction	Fraction of wind from a class "c" site in region "i" that is supplied to interconnect "in" that cannot be used because there is excess generation
$IWSurplusMar_{c,i,in}$	fraction	The fraction of wind generation lost from the next unit of class c wind installed in region i because there is no remaining load to be met by the wind in interconnect in
$IWSurplusOld_{in}$		The fraction of wind generation lost from all the wind installed to date in interconnect in because there is no remaining load to be met by the wind in interconnect in
j	integer	Subscript indicating a wind supply/demand region
L	years	Loan period
$L_{m,n}$	MW	The load in time slice m in PCA n
$loadgrowth_n$		The annual rate of load growth for PCA n
$lowsulcoalold_{n,q}$	MWh	Variable for the amount of electricity generated from low-sulfur coal in PCA n by coal technology q in the previous 2-year time period
$learnpar_q$	fraction	The learning parameter for wind or the reduction in the capital cost of wind for each doubling of the installed capacity
LP_{pol}	tons/year or lbs/year	The national annual cap on pollutant pol
L_q	years	The economic lifetime of technology q
$ltime_q$		The assumed operational lifetime in years of capacity of type q

LW	years	Lifetime of the wind plant[10]
m	integer	Subscript for the time slice
m’ and m”		The shoulder time slices within each season (summer, winter, spring, and fall)
$MINSR_q$	fraction	The fraction of each type of plant q that must be on line and loaded in order to serve as spinning reserve
$M_{n,p}$		Zero-one parameter indicating whether PCAs n and p are within 600 miles of one another
MTDF		Must-run conventional capacity, defined as existing available (i.e., not in a forced outage state) coal and nuclear capacity times a minimum turn down fraction
$MW\_inregion\_dis_{c,escp,j}$	$/MWh	Levelized cost from the escp step of the supply curve for the cost of building a transmission line from a class c onshore wind site to a load center within region i
$MW\_inregion\_disofd_{c,escpofd,j}$	$/MWh	Levelized cost from the escpofd step of the supply curve for the cost of building a transmission line from a class c deep offshore wind site to a load center within region i
$MW\_inregion\_disofs_{c,escpofs,j}$	$/MWh	Levelized cost from the escpofs step of the supply curve for the cost of building a transmission line from a class c shallow offshore wind site to a load center within region i
$NERCRm_r$		Reserve margin requirement in NERC region r
$NOR2_r$		The variance of the usual operating reserve requirement in NERC region r
Norfrac		The normal operating reserve fraction per MW of load
Norhydro		The amount by which the operating reserve can be reduced for each MW of hydroelectricity in the region
NOR_r		Normal operating reserve standard deviation in NERC region r
$numhoursbyseason_s$		Number of hours in season s
$numpeakhoursbyseason_s$		Number of peak hours in season s
$old\_grid\_2\_welectrolysis_{i,m}$		Electricity from the grid in region i consumed in time slice m by wind-sited electrolyzers built in previous periods
$optime_{mm}$		Off-peak time slice mm

[10] The wind lifetime is used to adjust the capital cost by the ratio of CRF(d,E)/CRF(d,LW) to account for any difference in lifetimes between wind and the economic evaluation period, E.

ordyear	years	Year of the optimization minus 2000 (i.e, the number of years since the beginning of the simulation)
$PCAdmdPK_n$		Peak demand in PCA n in 2000
$PCOSTFRAC_q$	1+fraction	Multiplier on operating/fuel cost associated with the operation of a thermal base-load unit at a higher level during the peak period than in the shoulder periods, e.g. cycling, ramping costs
P_n	MW	Peak load in PCA n
P_t		The principal portion of the finance payment made after the loan has been in place t years
POSTSTWCOST	$/MWh	Cost for transmitting power across a PCA
$PostStamp_{i,j}$	integer	Number of PCAs between wind regions i and j that must be crossed for wind power to be transmitted from i to j
$PostStamp_{n,p}$	integer	Number of PCAs between PCAs n and p that must be crossed for power to be transmitted from n to p
$PRETIRE_{n,q}$		The planned retirement in this period in PCA n of capacity of type q
PTCP	10 / years	Production tax credit period (use 10)
$ptime_m$		A binary constant equal to 1 when m is a peak-load time slice, 0 otherwise
$PVA_{d,E}$		Present value of annual $1 payments for E years
$PVA_{name,d,E,n}$		Present value of annual fuel costs for technology q in PCA n escalating annually for E years
PVDebt		The after-tax present value of debt payments
PVDep		The present value of depreciation
$QS_{n,q}$	MW	A variable for the capacity of type q in PCA n that has been modified to provide quick start capability
$RegDmd_{j,m}$		The electric load in region j in each hour of time slice m in the year 2000
$REMSCHED_{n,q}$		The remaining scheduled planned retirements in future periods in PCA n of capacity of type q
resconfint		Operating reserve minimum expressed in terms of the number of standard deviations of operating reserve required
RPSFrac	fraction	National Renewable Portfolio Standard level expressed as a fraction of annual national electric generation

RPSSCost	\$/MWh	Penalty imposed on utilities for not meeting the national RPS requirement
RPS_Shortfall	MWh	A variable for the additional amount of wind generation needed to meet the national RPS requirement beyond that supplied
SMRGR($HSMRBP_k$)		Breakpoints that discretize the SMR growth price penalty
SMRretper		The period during which the older remaining (i.e not yet retired) SMR were constructed
$SR_{m,n,q}$	MWh	Spinning reserve capacity during time period m in PCA n from technology q
$steam\_ref\_emiss_{pol}$	tons or pounds	Emissions of pollutant pol per MMBtu of gas input to steam methane reforming
$ST\_RPSSCost_{states}$	\$/MWh	Penalty imposed on utilities for not meeting the RPS requirement in states
$ST\_RPS\_Shortfall_{states}$	MWh	A variable for the additional amount of wind generation needed to meet the RPS requirement beyond that supplied in states
T_delay		The time required for learning to impact the market, i.e. the learning delay in periods between installations and cost reductions
TLOSS	fraction	Fraction of conventional power lost in each mile of transmission
Tk	MW	Capacity of transmission line k
TNCost	\$/MW-mile	Cost of new transmission lines
TNWCost	\$/MW-mile	Cost of new wind transmission lines
TOCost	\$/MWh-mile	Cost of transmission on existing lines
TOWCost	\$/MWh-mile	Cost of wind transmission on existing lines
$TPCA\_CG_{tpca\_g}$	\$/MW-mile	Difference between the price and cost of new transmission, due to rapid growth in transmission installations
$TPCA\_Ct_{tpca\_g}$	MW	A variable for the new transmission capacity in growth bin tpca_g
$TPCA\_Gt_{tpca\_g}$		A fractional multiplier of the national transmission (MW) capacity BASETPCA used to establish the size of growth bin tpca_g
TPCA_GP		The percent increase in the cost of transmission for each percent growth over the base amount
$TPCAN_{n,p}$	MW	New transmission line capacity built to carry new generation between PCA n and PCA p
$TPCAO_{n,p}$	MW	The transmission capacity between n and p that existed at the start of the period.
TR	fraction	Combined federal and state income tax rate

TR_j	MW	Capacity of transmission lines crossing the boundaries of wind supply region j
TWLOSS	fraction	The fraction of wind power lost in each mile of transmission.
$VCcoal_{n,q}$		The variable cost of operating a coal plant of type q in PCA n this period
WCC_c	$/MW	The overnight capital cost of a class c wind plant
WCt_g	MW	A variable for new onshore national wind turbine capacity in bin g; used for estimating the increase in wind turbine price with rapid world growth
$WCtinst_{ginst,i}$	MW	A variable for new onshore wind turbine capacity from bin ginst in region i; used for estimating the increase in installation costs with rapid regional growth
$WCVmar_{c,i,r}$	fraction	(Wind Capacity Value – marginal) The effective load-carrying capacity of 1 MW at a new wind farm at a class c site in region i delivered to NERC region r
$WCVold_r$	fraction	(Wind Capacity Value – old) The effective load-carrying capacity of all the wind capacity installed in previous periods whose generation is transmitted to NERC region r
$WELEC\_inregion_{c,escp,i}$	MW	A variable for new onshore wind turbine capacity from a class c wind site within region i from step escp of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$WELEC\_inregionofd_{c,escpofd,i}$	MW	A variable for new deep offshore wind turbine capacity from a class c wind site within region i from step escpofd of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$WELEC\_inregionofs_{c,escpofs,i}$	MW	A variable for new shallow offshore wind turbine capacity from a class c wind site within region i from step escpofs of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$wind\_2\_electrolysis_{c,i,s}$	MWh	A variable for class c onshore wind generation from new wind turbines that connect to the grid (not directly to load-distribution systems) supplied to a new

		conversion to storage process (e.g., electrolyzer/hydrogen storage) in region i in season s
$wind\_2\_electrolysis\_inregion_{c,i,s}$	MWh	A variable for onshore wind-generated electricity in season s from class c new turbines in region i that goes to storage (e.g., electrolyzer/hydrogen storage) at a wind site that is not connected to the grid, but is connected by new lines directly to the distribution system at a load center
$WindCap_{T\_delay}$		The total national installed wind capacity T_delay periods ago
$WN_{i,j}$	MW	A variable for new onshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
$WNofd_{i,j}$	MW	A variable for new deep offshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
$WNofs_{i,j}$	MW	A variable for new shallow offshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
$WNSC_{i,wscp}$	MW	A variable for new onshore wind turbine capacity to be connected to the grid in region i from step wscp of the supply curve, which provides the cost of building transmission from region i to the grid
$WNSCofd_{i,wscpofd}$	MW	A variable for new deep offshore wind turbine capacity to be connected to the grid in region i from step wscpofd of the supply curve, which provides the cost of building transmission from region i to the grid
$WNSCofs_{i,wscpofs}$	MW	A variable for new shallow offshore wind turbine capacity connected to the grid in region i from step wscpofs of the supply curve, which provides the cost of building transmission from region i to the grid
$WO_{c,i,j}$	MW	Existing (from the preceding time period) class c onshore wind on existing (at start of the simulation) transmission lines from region i to region j
$WOofd_{c,i,j}$	MW	Existing (from the preceding time period) class c deep offshore wind on existing (at start of the simulation) transmission lines

		from region i to region j
$WOofs_{c,i,j}$	MW	Existing (from the preceding time period) class c shallow offshore wind on existing (at start of the simulation) transmission lines from region i to region j
$WOMF_c$	$/MW-yr	Fixed annual O&M cost of class c wind
$WOMV_c$	$/MWh	Variable operating cost of class c wind
wor2factor		A multiplier on the wind variance to provide the appropriate impact on operating reserve requirements
$WORmar_{c,i,r}$		The operating reserve requirement induced by the marginal addition of one MW of class c wind in region i that is consumed in NERC region r
$WORold_{c,r}$		The average operating reserve induced per MW of existing class c wind that is consumed in NERC region r
$WORold_r$		The operating reserve requirement induced by all wind installed in previous periods that contributes to NERC region r
WPTC	$/MWh	Wind federal production tax credit
$WR2G_{c,i,wscp}$	MW	New onshore class c wind resource in region i available at interconnection cost step wscp
$WR2Gofd_{c,i,wscpofd}$	MW	New deep offshore class c wind resource in region i available at interconnection cost step wscpofd
$WR2Gofs_{c,i,wscpofs}$	MW	New shallow offshore class c wind resource in region i available at interconnection cost step wscpofs
$WR2GPTS_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c onshore wind resource in region i in supply curve step wscp
$WR2GPTSofd_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c deep offshore wind resource in region i in supply curve step wscpofd
$WR2GPTSofs_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c shallow offshore wind resource in region i in supply curve step wscpofs
WROW		The wind capacity installed in the rest of the world T_delay periods ago
$WRUC_{c,i}$	MW	Class c onshore wind resource in region i
$WRUCofd_{c,i}$	MW	Class c offshore deep wind resource in region i
$WRUCofs_{c,i}$	MW	Class c offshore shallow wind resource in

		region i
$WS_{j,m}$	MW	A variable for the amount by which the wind power supplied to region j exceeds the electricity demand in region j in time slice m
$WT_{n,p}$	MW	A variable for the new wind transmitted from PCA n to PCA p[11]
$WTN_{i,j}$	MW	A variable for new onshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTNofd_{i,j}$	MW	A variable for new deep offshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTNofs_{i,j}$	MW	A variable for new shallow offshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTO_{c,i,j}$	MW	Existing (at start of this time period) class c onshore wind on new transmission lines from region i to region j
$WTOofd_{c,i,j}$	MW	Existing (at start of this time period) class c deep offshore wind on new transmission lines from region i to region j
$WTOofs_{c,i,j}$	MW	Existing (at start of this time period) class c shallow offshore wind on new transmission lines from region i to region j
$Wtur\_inregion_{c,i}$	MW	A variable for new onshore wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i
$Wtur\_inregionofd_{c,i}$	MW	A variable for new deep offshore wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i
$Wtur\_inregionofs_{c,i}$	MW	A variable for new shallow offshore wind turbine capacity whose transmitted electricity will move on new transmission lines

[11] Without this variable, WinDS will ship power from wind supply region i to the closest wind demand region j; and, from there, continue to ship it as conventional power to other PCAs where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different PCA, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

		dedicated to wind from a class c wind site within region i to a load center also within region i
$WturN_{i,wscp}$	MW	A variable for new onshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscp of the transmission supply curve
$WturNofd_{i,wscpofd}$	MW	A variable for new deep offshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscpofd of the transmission supply curve
$WturNofs_{i,wscpofs}$	MW	A variable for new shallow offshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscpofs of the transmission supply curve
$WturO_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c onshore wind transmitted on existing lines from region i
$WturOofd_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c deep offshore wind transmitted on existing lines from region i
$WturOofs_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c shallow offshore wind transmitted on existing lines from region i
$WTturO_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c wind transmitted on new transmission lines from region i
$WTturOofd_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) deep offshore wind on new transmission lines
$WTturOofs_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) shallow offshore wind on new transmission lines
$WturTN_i$	MW	A variable for new onshore wind turbine capacity that can be transmitted only on new transmission lines dedicated to wind transmission from region i to another region
$WturTNofd_i$	MW	A variable for new deep offshore wind turbine capacity that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region
$WturTNofs_i$	MW	A variable for new shallow offshore wind turbine capacity that can only be transmitted

		on new transmission lines dedicated to wind transmission from region i to another region
W_UScapyr2000		The total national wind capacity in the year 2000
γ	1.96	Confidence interval parameter (95%)

Appendix B

Geographic Information System (GIS) Calculations

Using Geographic Information Systems (GIS), a preliminary optimization is performed outside and prior to the linear programming model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each region i and wind class c.

The pre-optimization has the form:

Minimize $$\sum_{l,c,h,i,k}(GC_{l,c} + TC_{lchik}) * W_{lchik} + \sum_{k} M * D_k$$

Where:

GCl,c is the levelized cost of generation from a wind farm of type l (onshore, offshore shallow, and offshore deep) at a class c wind resource site

TC_{lchik} is the levelized cost of building a transmission spur for class c wind of type l from grid square h in region i to transmission line k

W_{lchik} is class c wind of type l transported from grid square h in region i on transmission line k.

M is a large number (very high cost)

D_k is a dummy variable to ensure feasibility in the constraint below

Subject to:

$$\sum_{l,c,h,i,k} W_{lchik} + D_k \geq a_k * T_k$$

where: **a_k** is the fraction of the capacity (**T_k**) of line k available

Using the results of this pre-optimization, supply curves are constructed for each region i, for each type of wind resource l (onshore, shallow offshore, and deep offshore) and for each class of wind resource within that type. Each supply curve is made up of four wind resource/cost pairs identified by the subscript $_{wscp}$ where wscp takes on the values 1 through 4. The amount of wind resource in each step is set initially so that for each type of wind l:

$$\mathrm{WR2G}_{l,c,i,wscp} = f_{wscp} * \sum_{h,k} W_{lchik}$$

where $f_1 = 0.10$
$f_2 = 0.20$
$f_3 = 0.30$
$f_4 = 0.40$

Thus, the first step on the supply curve is comprised of the 10% of all the class c wind grid squares in region i with the lowest cost to build transmission spurs to the grid. The next step consists of the 20% with the next lowest set of costs, etc. The cost, $WR2GPTS_{l,c,i,wscp}$, associated with each point or step on the supply curve is the mean levelized transmission spur cost for that step.

The supply curve quantity/price pairs – $WR2G_{l,c,i,wscp}$ and $WR2GPTS_{l,c,i,wscp}$ – from this pre-LP optimization are input to the linear programming WinDS model within the "Transmission Constrained Wind Resource" constraints. In each period, the quantities, $WR2G_{l,c,i,wscp}$, are decremented by the amount of wind resource in that step deployed in previous periods.

Ideally, this preoptimization should be performed for each period of the WinDS run with the costs of wind generation specific to that period (wind generation costs generally decrease from one period to the next either because of exogenously specified R&D-driven reductions in capital and operating costs, and/or because of learning through industrial experience). This is not possible because of time and computer resources required to conduct this optimization in GIS for the large number of wind grid squares considered. Currently, the optimization is conducted once using the wind cost/performance characteristics for the first period.